

RELATIONAL GRAPH MODELS AT WORK

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ABSTRACT. We study the relational graph models that constitute a natural subclass of relational models of λ -calculus. We prove that among the λ -theories induced by such models there exists a minimal one, and that the corresponding relational graph model is very natural and easy to construct. We then study relational graph models that are fully abstract, in the sense that they capture some observational equivalence between λ -terms. We focus on the two main observational equivalences in the λ -calculus, the theory \mathcal{H}^+ generated by taking as observables the β -normal forms, and \mathcal{H}^* generated by considering as observables the head normal forms. On the one hand we introduce a notion of λ -König model and prove that a relational graph model is fully abstract for \mathcal{H}^+ if and only if it is extensional and λ -König. On the other hand we show that the dual notion of *hyperimmune* model, together with extensionality, captures the full abstraction for \mathcal{H}^* .

INTRODUCTION

The untyped λ -calculus is a paradigmatic programming language introduced by Church in [24], having a prominent role in theoretical computer science [6] since, despite its very simple syntax, it is Turing-complete. Its denotational models have been fruitfully used for proving the consistency of extensions of β -convertibility, called λ -theories, and for exposing operational features of λ -terms. The first model of λ -calculus, \mathcal{D}_∞ , was defined by Scott in the pioneering article [75]. Subsequently, a wealth of models have been introduced in various categories of domains and classified into *semantics* according to the nature of their representable functions. Scott's *continuous semantics* [76] corresponds to the category whose objects are complete partial orders and morphisms are continuous functions. The *stable semantics* [11] and the *strongly stable semantics* [18] are refinements of the continuous semantics, introduced to capture the notion of “sequential” continuous function. In each of these semantics all the models come equipped with a partial order, and some of them, called *webbed models*, are built from lower level structures called “webs” [9]. The simplest class of webbed models is the class of *graph models* [57], which was isolated in the seventies by Plotkin, Scott and Engeler within the continuous semantics [38, 67, 76].

In each of the aforementioned semantics there exists a continuum of models inducing pairwise distinct λ -theories. Nevertheless, certain models are particularly important because they allow to capture operational properties of the λ -terms. For instance, two λ -terms have the same interpretation in Engeler's graph model \mathcal{E} exactly when they are equal in the λ -theory \mathcal{B} , which equates all λ -terms having the same Böhm tree. The main technical tool

for proving such a result is the Approximation Theorem [44], stating that the interpretation of a λ -term is given by the supremum of the interpretations of the finite approximants of its Böhm tree. Other models are significant because they are *fully abstract*, which means that the induced λ -theory captures some observational equivalence between λ -terms. A celebrated result by Hyland [46] and Wadsworth [82] shows that Scott's \mathcal{D}_∞ is fully abstract for the λ -theory \mathcal{H}^* , that corresponds to the observational equivalence where the observables are the head normal forms. In [25], Coppo, Dezani-Ciancaglini and Zacchi constructed a *filter model* \mathcal{D}_{cdz} and proved that it is fully abstract for \mathcal{H}^+ , the observational equivalence where the observables are the β -normal forms. The λ -theory \mathcal{H}^+ is the original extensional observational theory defined by Morris in his thesis [64]. It is maybe less ubiquitously studied in the literature than \mathcal{H}^* but we believe it equally important. For instance, its notion of observables is central in the Böhm Theorem [13] and in other separability results [27].

Graph Models in the Relational Semantics. In the present paper we focus on the *relational semantics* of λ -calculus, that has been introduced by Girard as a quantitative model of linear logic in [42]. The first concrete examples of relational models of λ -calculus were built in [19, 48]. Recently, Manzonetto and Ruoppolo individuated the subclass of *relational graph models* encompassing all previous examples [62]. The definition of a relational graph model (Definition 3.4) really is the relational analogue of the definition of a graph model living in the continuous semantics. In particular, relational graph models can be built by free completion and by forcing like the continuous ones. However, from the point of view of the induced λ -theories, they share more similarities with filter models. For instance, the relational graph model \mathcal{D}_ω built in [19] has the same theory as Scott's \mathcal{D}_∞ , namely it is fully abstract for \mathcal{H}^* [60]. Similarly, the model \mathcal{D}_\star from [62] is fully abstract for \mathcal{H}^+ , like the filter model \mathcal{D}_{cdz} . On the other hand, no graph model living in the continuous semantics can represent such λ -theories because no graph model is extensional. When comparing relational graph models with filter models inducing the same λ -theory, one can see that the former are in general simpler because their elements are not partially ordered. Moreover, an element σ in the relational interpretation of a λ -term M carries information concerning intensional properties of M . In particular, from σ it is possible to compute a bound to the number of head-reduction steps towards its normal form and infer the amount of resources consumed by M during such a reduction sequence [29, 30].

Relational Graph Models as Type Systems. The Stone duality between filter models and intersection type systems has been widely studied in the literature, e.g., [1, 26, 44, 8, 74]. (We refer to Ronchi Della Rocca and Paolini's book for a thoughtful discussion [71, Ch 13].) Such a correspondence shows that some interesting classes of domain-based models can be described in logical form. The intuition is that a functional intersection type $\alpha_1 \wedge \dots \wedge \alpha_n \rightarrow \beta$ can be seen as a continuous step function sending the set $\{\alpha_1, \dots, \alpha_n\}$ to the element β . Types come equipped with inference rules reflecting the structure of the underlying domain. In [66], Paolini et al. introduced the *strongly linear* relational models (a class encompassing relational graph models, but included in the *linear* relational models of [61]) and show that they can be represented as relevant (i.e., without weakening) intersection type systems where the intersection is a non-idempotent operation (it is actually a linear logic tensor \otimes). The idea, already present in [29], is that in the absence of idempotency and partial orders the type $\alpha_1 \wedge \dots \wedge \alpha_n \rightarrow \beta$ can be seen as a relation associating the multiset $[\alpha_1, \dots, \alpha_n]$ with the element β . As a consequence of the work in [66], all relational graph models can

be presented in logical form, that is, as non-idempotent intersection type systems. We use this kind of representation to expose and exploit their quantitative features.

The Approximation Theorem. Besides soundness (Theorem 3.15), one of the main properties enjoyed by relational graph models is the Approximation Theorem (Theorem 4.15). Typically such a theorem is proved by exploiting Wadsworth’s stratified refinements of the β -reduction [82], that also work in the relational framework as shown in [60]. Other techniques are based on Tait and Girard’s *reducibility candidates* [79, 41], that are widespread in logic and the theory of programming languages [69, 52, 53, 8], but notoriously give rise to impredicative proofs. Thanks to its quantitative nature, in the context of the relational semantics it is possible to get rid of the traditional methods and provide a combinatorial proof. This is the case of the proof given in [62] by relying on the following facts:

- Relational graph models are also models of Ehrhard and Regnier’s *resource/differential calculus* [36, 80]. This follows from the fact that they all are *linear* reflexive objects in the cartesian closed differential category **MRel** [61].
- An easy induction shows that the interpretation of a λ -term M in a relational graph model is equal to the interpretation of its *Taylor expansion* [36], which is a representation of M as a power series of resource approximants (replacing in a way the finite approximants of its Böhm tree).
- The usual Approximation Theorem follows from the above result by applying a theorem due to Ehrhard and Regnier [37] stating that the normal form of the Taylor expansion of M coincides with the Taylor expansion of its Böhm tree.

In Section 4.5 we provide a new combinatorial proof of the Approximation Theorem by exploiting the logical presentation discussed above. We are going to associate a measure with the derivation tree π of $\Gamma \vdash M : \alpha$ and show that when M β -reduces to N by contracting a redex R two cases are possible: either there exists a derivation of $\Gamma \vdash N : \alpha$ having a strictly smaller measure, or π is a derivation of $\Gamma \vdash M\{\perp/R\} : \alpha$, where $M\{\perp/R\}$ denotes the approximant obtained by substituting a constant \perp for the redex R in M . In both cases, either the measure of the derivation or the number of redexes in M has decreased. Therefore the Approximation Theorem follows by a simple induction over the ordinal ω^2 .

The Minimal Relational Graph Theory. Every relational graph model induces a λ -theory through the kernel of its interpretation function. We call *relational graph theories* those λ -theories induced by some relational graph models. A natural question that arises is what λ -theories are in addition relational graph theories. We do not provide a characterization, but we show that the λ -theories \mathcal{B} , \mathcal{H}^+ and \mathcal{H}^* are. Another question is whether there exists a minimal relational graph theory: for instance, in [21] Bucciarelli and Salibra proved that the minimal λ -theory among the ones represented by usual graph models exists, but their construction of the minimal model is complicated and what λ -terms are actually equated in the minimal theory remains a mystery. In Section 5 we show not only that a minimal relational graph theory exists, but also that such a λ -theory is actually \mathcal{B} . Also, the corresponding model \mathcal{E} is very simple to define (its construction is actually analogous to the one of Engeler’s graph model). Moreover, we prove that even the preorder induced by \mathcal{E} on λ -terms is minimal among representable inequational theories. Our model \mathcal{E} shares many properties with Ronchi Della Rocca’s filter model defined in [70].

Characterizing Fully Abstract Models. In the literature there are many full abstraction theorems, namely results showing that some observational equivalence arises as the theory of a suitable denotational model. However, until recently, researchers were only able to prove full abstractions for individual models [46, 82, 25], or at best to provide sufficient conditions for models living in some class to be fully abstract [60, 43]. A substantial advance was made in [15], where Breuvert proposed a notion of *hyperimmune* model of λ -calculus, and showed that a K -model¹ living in the continuous semantics is fully abstract for \mathcal{H}^* if and only if it is extensional and hyperimmune, thus providing a characterization. In Section 6 we define the dual notion of λ -*König* model and prove that a relational graph model is fully abstract for \mathcal{H}^+ exactly when it is extensional and λ -König. Subsequently, in Section 7, we show that the notion of hyperimmune continuous model has a natural counterpart in the relational semantics and that, also in the latter case, together with extensionality gives a characterization of all relational graph models fully abstract for \mathcal{H}^* .

Related Works. The primary goal of this article is to provide a uniform and self-contained treatment of relational graph models and their properties. In particular, we present some semantical results recently appeared in the conference papers [62, 17]. (The syntactic results in [17] will be the subject of a different paper [49] in connection with the ω -rule.) Besides giving more detailed proofs and examples, we provide several original results, like a quantitative proof of the Approximation Theorem, the characterization of the minimal representable theory, and the characterization of all relational graph models that are fully abstract for \mathcal{H}^* . A natural comparison is with the article [66], where Paolini *et al.* introduce the notion of strongly linear relational model and show that such models correspond to their notion of *essential* type systems. We remark that their work rather focuses on the properties enjoyed by those systems, like (weighted) subject reduction/expansion and adequacy, while we focus on the representable λ -theories and provide general full abstraction results.

The relational semantics, being very versatile, can also be used to model the call-by-value and the call-by-push-value λ -calculus [56], as well as non-deterministic [31, 32, 3] and resource sensitive extensions [36, 37] of λ -calculus. We refer the reader to [34, 23] for a relational semantics of the call-by-value λ -calculus and to [35] for the call-by-push-value. For non-deterministic calculi, see [20] in the call-by-name setting and [33] in the call-by-value one. Relational models of differential and resource calculi have been studied in [65, 61, 14]. The relational semantics has been generalized by considering multisets with infinite multiplicities to build non-sensible models [22], and by replacing relations with matrices of scalars to provide quantitative models of non-deterministic PCF [54]. An even more abstract perspective, where the categorical notion of profunctors takes the role of relations, was contemplated in [39, 47].

Outline. In Section 1 we present some notions and notations, mainly concerning λ -calculus, that are useful in the rest of the article. In Section 2 we review some literature concerning the observational equivalences corresponding to \mathcal{H}^+ and \mathcal{H}^* , and their characterizations in terms of extensional equivalences on Böhm trees. In Section 3 we define the class of relational graph models, show how to build them via free completion of a partial pair, and prove the soundness. In Section 4 we provide the presentation of relational graph models in logical form, exhibit their quantitative features and prove the Approximation Theorem.

¹The class of K -models, which contains all graph models, was isolated by Krivine in [52].

Section 5 is devoted to present the relational graph model having minimal (inequational) theory, and to prove that the induced theory is actually minimal. Finally, in Section 6 and Section 7 we provide the characterizations of all relational graph models that are fully abstract for \mathcal{H}^+ and \mathcal{H}^* , respectively.

1. PRELIMINARIES

1.1. Sets, Functions and Multisets. We denote by \mathbb{N} the set of natural numbers and by \mathbb{N}^+ the set of strictly positive natural numbers.

Let A, B be two sets. We write $\mathcal{P}(A)$ for the powerset of A , and $\mathcal{P}_f(A)$ for the set of all finite subsets of A . Given a function $f : A \rightarrow B$ we write $\text{dom}(A)$ for its *domain*.

A *multiset* over A is a partial function $a : A \rightarrow \mathbb{N}^+$. Given $\alpha \in A$ and a multiset a over A , the *multiplicity of α in a* is given by $a(\alpha)$. A multiset a is called *finite* if $\text{dom}(a)$, which is called its *support*, is finite. A finite multiset a will be represented as an unordered list of its elements $[\alpha_1, \dots, \alpha_n]$, possibly with repetitions. The empty multiset is denoted by ω . We write $\mathcal{M}_f(A)$ for the set of all finite multisets over A . Given $a_1, a_2 \in \mathcal{M}_f(A)$, their *multiset union* is denoted by $a_1 + a_2$ and defined as a pointwise sum.

1.2. Sequences and Trees. We denote by $\mathbb{N}^{<\omega}$ the set of finite sequences over \mathbb{N} . An arbitrary sequence is of the form $\sigma = \langle n_1, \dots, n_k \rangle$. The empty sequence is denoted by ε .

Let $\sigma = \langle n_1, \dots, n_k \rangle$ and $\tau = \langle m_1, \dots, m_{k'} \rangle$ be two sequences and let $n \in \mathbb{N}$. We write:

- $\sigma.n$ for the sequence $\langle n_1, \dots, n_k, n \rangle$,
- $\sigma \cdot \tau$ for the concatenation of σ and τ , that is for the sequence $\langle n_1, \dots, n_k, m_1, \dots, m_{k'} \rangle$.

We say that σ is a *subsequence of τ* , denoted $\sigma \subseteq \tau$, when $\tau = \sigma \cdot \sigma'$ for some $\sigma' \in \mathbb{N}^{<\omega}$. Given a map $f : \mathbb{N} \rightarrow \mathbb{N}$, its *prefix of length n* is the sequence $\langle f|n \rangle := \langle f(0), \dots, f(n-1) \rangle$.

Definition 1.1 (Trees and subtrees).

- A *tree* is a partial function $T : \mathbb{N}^{<\omega} \rightarrow \mathbb{N}$ such that $\text{dom}(T)$ is closed under prefixes and for all $\sigma \in \text{dom}(T)$ and $n \in \mathbb{N}$ we have $\sigma.n \in \text{dom}(T)$ if and only if $n < T(\sigma)$.
- We write \mathbb{T} for the set of all trees.
- The *subtree of T at σ* is the tree $T|_\sigma$ defined by $T|_\sigma(\tau) = T(\sigma \cdot \tau)$ for all $\tau \in \mathbb{N}^{<\omega}$.

The elements of $\text{dom}(T)$ are called *positions*. For all $\sigma \in \text{dom}(T)$, $T(\sigma)$ gives the number of children of the node in position σ . Hence $T(\sigma) = 0$ when σ corresponds to a leaf.

Definition 1.2. A tree T is called:

- *recursive* if the function T is partial recursive (after coding);
- *finite* if $\text{dom}(T)$ is finite;
- *infinite* if it is not finite.

We denote by \mathbb{T}^∞ (resp. $\mathbb{T}_{\text{rec}}^\infty$) the set of all infinite (resp. recursive infinite) trees.

Definition 1.3 (Infinite paths). A function $f : \mathbb{N} \rightarrow \mathbb{N}$ is an *infinite path of T* if $\langle f|n \rangle \in \text{dom}(T)$ for all $n \in \mathbb{N}$. We denote by $\Pi(T)$ the set of all infinite paths of T .

By König's lemma, a tree T is infinite if and only if $\Pi(T) \neq \emptyset$.

1.3. Category Theory. Concerning category theory we mainly use the notations from [4].

Let \mathbf{C} be a category and A, B, C be arbitrary objects of \mathbf{C} . We write $\mathbf{C}(A, B)$ for the homset of morphisms from A to B . When there is no chance of confusion we simply write $f : A \rightarrow B$ instead of $f \in \mathbf{C}(A, B)$. Given two morphisms $f : A \rightarrow B$ and $g : B \rightarrow C$, their composition is indicated by $g \circ f : A \rightarrow C$.

When the category \mathbf{C} is Cartesian, we denote by \top the *terminal object*, by $A \times B$ the *categorical product* of A and B , by $\pi_1 : A \times B \rightarrow A$, $\pi_2 : A \times B \rightarrow B$ the associated *projections* and, given a pair of arrows $f : C \rightarrow A$ and $g : C \rightarrow B$, by $\langle f, g \rangle : C \rightarrow A \times B$ the unique arrow such that $\pi_1 \circ \langle f, g \rangle = f$ and $\pi_2 \circ \langle f, g \rangle = g$. We write $f \times g$ for the *product map of f and g* which is defined by $f \times g = \langle f \circ \pi_1, g \circ \pi_2 \rangle$.

When \mathbf{C} is in addition *Cartesian closed* we write $A \Rightarrow B$ for the *exponential object* and $\text{ev}_{AB} : (A \Rightarrow B) \times A \rightarrow B$ for the *evaluation morphism*. Moreover, for any object C and arrow $f : C \times A \rightarrow B$, $\Lambda(f) : C \rightarrow (A \Rightarrow B)$ stands for the (unique) morphism such that $\text{ev}_{AB} \circ (\Lambda(f) \times \text{Id}_A) = f$.

A Cartesian closed category \mathbf{C} is *well-pointed* if, for all objects A, B and morphisms $f, g : A \rightarrow B$, whenever $f \neq g$, there exists a morphism $h : \top \rightarrow A$ such that $f \circ h \neq g \circ h$. Similarly, an object A is *well-pointed* if the property above holds for all $f, g : A \rightarrow A$.

We say that $\mathcal{D} = (D, \text{App}, \lambda)$ is a *reflexive object (living in \mathbf{C})* if D is an object of \mathbf{C} and $\text{App} : D \rightarrow (D \Rightarrow D)$, $\lambda : (D \Rightarrow D) \rightarrow D$ are morphisms such that $\text{App} \circ \lambda = \text{Id}_{D \Rightarrow D}$. A reflexive object \mathcal{D} is called *extensional* whenever $\lambda \circ \text{App} = \text{Id}_D$.

1.4. The Lambda Calculus. We generally use the notation of Barendregt's book [6] for λ -calculus. The set Λ of λ -terms over a denumerable set Var of variables is defined by:

$$\Lambda : \quad M, N, P, Q ::= x \mid \lambda x.M \mid MN \quad \text{for all } x \in \text{Var}.$$

We assume that the application associates to the left and has a higher precedence than λ -abstraction. For instance, we write $\lambda xyz.xyz$ for the λ -term $\lambda x.(\lambda y.(\lambda z.((xy)z)))$. Moreover, we often write \vec{x} for the sequence $\langle x_1, \dots, x_n \rangle$ and $\lambda \vec{x}.M$ for $\lambda x_1 \dots \lambda x_n.M$.

The set $\text{FV}(M)$ of *free variables* of M and the α -conversion are defined as in [6, Ch. 1§2]. Hereafter, we consider λ -terms up to α -conversion.

Definition 1.4. A λ -term M is *closed* whenever $\text{FV}(M) = \emptyset$ and in this case it is also called a *combinator*. The set of all combinators is denoted by Λ° .

We often consider relations on λ -terms that have the property of being “context closed”. Intuitively a context $C[-]$ is a λ -term with a *hole* denoted by $[-]$. Formally, the hole is an algebraic variable and contexts are defined as follows.

Definition 1.5.

- A *context* $C[-]$ is generated by the grammar (for $x \in \text{Var}$):

$$C[-] ::= [-] \mid x \mid \lambda x.C[-] \mid (C_1[-])(C_2[-])$$

- A context $C'[-]$ is called *single hole* if it has a unique occurrence of the algebraic variable $[-]$. Single hole contexts are generated by (for $M \in \Lambda$):

$$C'[-] ::= [-] \mid \lambda x.C'[-] \mid M(C'[-]) \mid (C'[-])M$$

- A context $H[-]$ is a *head context* if it has the shape $(\lambda x_1 \dots \lambda x_n.[-])M_1 \dots M_k$ for some $n, k \geq 0$ and $M_1, \dots, M_k \in \Lambda$.

Given a context $C[-]$, we write $C[M]$ for the λ -term obtained from $C[-]$ by substituting M for the hole $[-]$ possibly with capture of free variables in M .

A relation $R \subseteq \Lambda \times \Lambda$ is *context closed* whenever $M R N$ entails $C[M] R C[N]$ for all contexts $C[-]$. The *context closure* of a relation $R \subseteq \Lambda \times \Lambda$ is the smallest context closed relation R' containing R .

Reductions. The λ -calculus is a higher-order term rewriting system, and several notions of reduction can be considered. As a matter of notation, given a reduction R , we write \rightarrow_R for its context closure, \rightarrow_R^* for the transitive and reflexive closure of \rightarrow_R , finally $=_R$ for the corresponding R -conversion, that is the transitive, reflexive and symmetric closure of \rightarrow_R . We denote by $\text{nf}_R(M)$ the R -normal form of M (if it exists) and by NF_R the set of all R -normal forms. Given two reductions R_1, R_2 we denote their union by simple juxtaposition, i.e. $\rightarrow_{R_1 R_2}$ represents the relation $\rightarrow_{R_1} \cup \rightarrow_{R_2}$.

The main notion of reduction is the β -reduction, which is the context closure of:

$$(\beta) \quad (\lambda x.M)N \rightarrow M\{N/x\}$$

where $M\{N/x\}$ denotes the capture-free simultaneous substitution of N for all free occurrences of x in M . The term on the left hand-side of the arrow is called β -redex, while the term on the right hand-side is its β -contractum.

A λ -term M is in β -normal form (β -nf, for short) if and only if $M = \lambda \vec{x}.x_i.M_1 \cdots M_k$ and each M_i is in β -nf. We say that M has a β -nf whenever $\text{nf}_\beta(M)$ exists.

It is well known that the λ -calculus is an intensional language — there are β -different λ -terms that are extensionally equal. This justifies the definition of the η -reduction:

$$(\eta) \quad \lambda x.Mx \rightarrow M \text{ provided } x \notin \text{FV}(M).$$

Notice, however, that, when M is a λ -abstraction, the η -reduction is actually a β -step.

Useful combinators and encodings. Concerning specific combinators, we fix the following notations:

$$\begin{aligned} \mathbf{I} &= \mathbf{1}_0 = \lambda x.x & \mathbf{K} &= \lambda xy.x & \mathbf{1}_{n+1} &= \lambda xy.x(\mathbf{1}_n y) \\ \mathbf{F} &= \lambda xy.y & \Delta &= \lambda x.xx & \mathbf{Y} &= \lambda f.(\lambda x.f(xx))(\lambda x.f(xx)) \\ &= \mathbf{c}_n & \lambda fz.f^n(z) &= \mathbf{J} & \mathbf{Y}(\lambda jxy.x(jy)) &= \end{aligned}$$

where $f^n(z) = f(\cdots f(f(z)) \cdots)$, n times. We will simply denote by $\mathbf{1}$ the combinator $\mathbf{1}_1 =_\beta \lambda xy.xy$. It is easy to check that \mathbf{I} is the identity, $\mathbf{1}_n$ is a $\beta\eta$ -expansion of the identity, \mathbf{K} and \mathbf{F} are respectively the first and second projection, $\mathbf{\Omega}$ is the paradigmatic looping combinator, \mathbf{Y} is Curry's fixed point combinator, \mathbf{c}_n is the n -th Church's numeral and \mathbf{J} is Wadsworth's "infinite η -expansion of the identity" (see Section 2).

Given two λ -terms M and N their *composition* is defined by $M \circ N = \lambda x.M(Nx)$ and their *pairing* by $[M, N] = \lambda x.xMN$ (for $x \notin \text{FV}(MN)$). Similarly, it is possible to λ -define a given enumeration $(M_n)_{n \in \mathbb{N}}$ of closed λ -terms whenever the enumeration is effective.

Definition 1.6. An enumeration of closed λ -terms $(M_n)_{n \in \mathbb{N}}$ is called *effective* (or *uniform* in [6]) if there is a combinator $F \in \Lambda^o$ such that $F\mathbf{c}_n =_\beta M_n$ for all n .

As shown in [6, Def. 8.2.3], when the enumeration is effective, the sequence $[M]_{n \in \mathbb{N}}$ can be expressed (using the fixed point combinator \mathbf{Y}) as a single λ -term satisfying

$$[M_n]_{n \in \mathbb{N}} =_\beta [M_0, [M_{n+1}]_{n \in \mathbb{N}}] =_\beta [M_0, [M_1, [M_{n+2}]_{n \in \mathbb{N}}]] =_\beta \cdots$$

Such infinite sequences will be mainly used in the following sections to build examples.

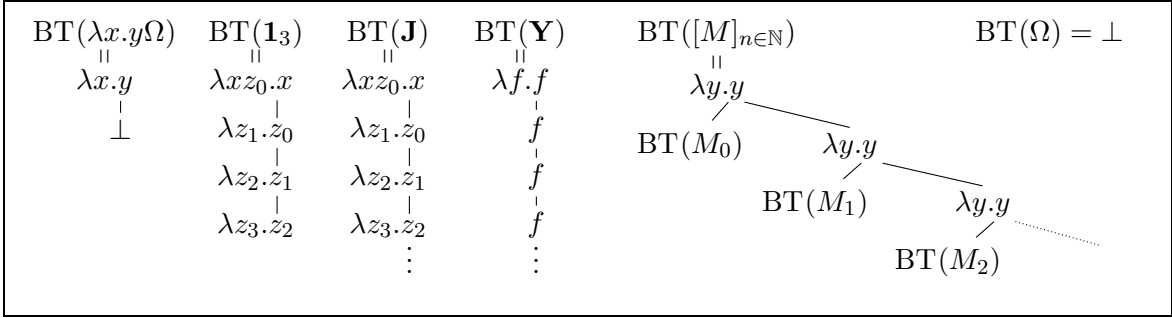


Figure 1: Some examples of Böhm trees.

Solvability. Lambda terms are classified into solvable and unsolvable, depending on their capability of interaction with the environment, represented here by a context.

Definition 1.7.

- A λ -term M is *solvable* if there exists a head context $H[-]$ such that $H[M] =_{\beta} \mathbf{I}$. Otherwise M is called *unsolvable*.
- Two λ -terms M, N are called *separable* if there exists a context $C[-]$ such that $C[M] =_{\beta} x$ and $C[N] =_{\beta} y$ for some variables $x \neq y$.
- Two λ -terms M, N are called *semi-separable* if there exists a context $C[-]$ such that $C[M]$ is solvable while $C[N]$ is unsolvable or *vice versa*.

Solvability has been characterized by Wadsworth in terms of *head normalization* in [81]. We recall that a λ -term M is in *head normal form* (*hnf*, for short) if it is of the form $M = \lambda x_1 \dots x_n. x_i. M_1 \dots M_k$ for $n, k \geq 0$, where either $i \leq n$ or x_i is free. A λ -term M *has a hnf* if it is β -convertible to a hnf. The *principal hnf* of a λ -term M , denoted $\text{phnf}(M)$, is the hnf obtained from M by *head reduction* \rightarrow_h , that is by repeatedly contracting the head redex $\lambda \vec{y}. (\lambda x. M) N \vec{P}$ in M . We refer to [6, Def. 8.3.10] for a formal definition.

Theorem 1.8 (Wadsworth [81]).

A λ -term M is solvable if and only if M has a head normal form.

We say that M, N have *similar hnf's* if $\text{phnf}(M) = \lambda x_1 \dots x_n. x_i. M_1 \dots M_k$ and $\text{phnf}(N) = \lambda x_1 \dots x_{n'}. x_{i'}. N_1 \dots N_{k'}$ with $k - n = k' - n'$ and either x_i is free or $i \leq \min\{n, n'\}$.

1.5. Böhm Trees. The Böhm trees, introduced by Barendregt in 1977 [5] and named after Corrado Böhm, are possibly infinite labelled trees representing the execution of a λ -term.

Definition 1.9. The *Böhm tree* $\text{BT}(M)$ of a λ -term M is defined coinductively as follows:

- if M is unsolvable then $\text{BT}(M) = \perp$;
- if M is solvable and $\text{phnf}(M) = \lambda x_1 \dots x_n. x_i. M_1 \dots M_k$ then:

$$\text{BT}(M) = \lambda x_1 \dots x_n. x_i \begin{array}{c} \diagdown \quad \diagup \\ \text{BT}(M_1) \quad \dots \quad \text{BT}(M_k) \end{array}$$

In Figure 1 we provide some notable examples of Böhm trees. Notice that in general $\text{FV}(\text{BT}(M)) \subseteq \text{FV}(M)$ but the converse may not hold. Indeed, given a λ -term M satisfying $M \rightarrow_{\beta} \lambda z. x. x(Mz)$, we have that $z \notin \text{FV}(\text{BT}(M))$ because z is “pushed to infinity”.

We also present, as an auxiliary notion, the “Böhm-like trees”, which are labelled trees that look like Böhm trees but may not arise as a Böhm tree of a λ -term.

Definition 1.10. A *Böhm-like tree* is a labelled tree over $\mathcal{L} = \{\perp\} \cup \{\lambda\vec{x}.y \mid \vec{x}, y \in \text{Var}\}$, that is a function $U : \mathbb{N}^{<\omega} \rightarrow \mathcal{L} \times \mathbb{N}$ such that $\pi_2 \circ U$ is a tree and $(\pi_1 \circ U)(\sigma) = \perp$ entails $(\pi_2 \circ U)(\sigma) = 0$. The tree $\pi_2 \circ U$ is called *the underlying tree of U* and is denoted by $\lfloor U \rfloor$.

A Böhm-like tree U is λ -definable if $U = \text{BT}(M)$ for some $M \in \Lambda$. In [6, Thm. 10.1.23], Barendregt gives the following characterization of λ -definable Böhm-like trees.

Theorem 1.11. Given a Böhm-like tree U , there exists a λ -term M such that $\text{BT}(M) = U$ if and only if U is partial computable (after coding) and $\text{FV}(U)$ is finite.

The Böhm tree \perp represents the absolute lack of information, therefore it makes sense to say that \perp is “less defined” than any Böhm-like tree U . This is the consideration behind the order \leq_\perp on Böhm-like trees defined below.

Definition 1.12. Given two Böhm-like trees U, V we say that U is an *approximant* of V , written $U \leq_\perp V$, whenever U results from V by replacing countably many subtrees by \perp .

Approximations of Böhm trees. A Böhm tree can be also seen as the least upper bound of its finite approximants, and finite approximants can be seen as the normal forms of a λ -calculus extended with a constant \perp and an additional reduction \rightarrow_\perp .

A $\lambda\perp$ -term M is a λ -term possibly containing occurrences of the constant \perp . The set Λ_\perp of all $\lambda\perp$ -terms is generated by the grammar:

$$\Lambda_\perp : \quad M, N ::= x \mid \lambda x.M \mid MN \mid \perp$$

Similarly a (single hole) $\lambda\perp$ -context is a (single hole) context $C[-]$ possibly containing occurrences of \perp . The \perp -reduction \rightarrow_\perp is defined as the $\lambda\perp$ -contextual closure of the rules:

$$(\perp) \quad \lambda x.\perp \rightarrow \perp \quad \perp M \rightarrow \perp$$

The β - and η - reductions are extended to $\lambda\perp$ -terms in the obvious way. We write $\text{NF}_{\beta\perp}$ for the set of $\lambda\perp$ -terms in $\beta\perp$ -normal forms and we denote its elements by s, t, u, \dots

The following characterization of $\beta\perp$ -normal forms is well known.

Lemma 1.13. Let $M \in \Lambda_\perp$. We have $M \in \text{NF}_{\beta\perp}$ if and only if either $M = \perp$ or M has shape $\lambda x_1 \dots x_n.x_i.M_1 \dots M_k$ (for some $n, k \geq 0$) and each M_i is $\beta\perp$ -normal.

Definition 1.14. The *size* of $t \in \text{NF}_{\beta\perp}$, written $\#t$, is defined by induction:

$$\#\perp = 0, \quad \#(\lambda x.t) = 1 + \#t, \quad \#(xt_1 \dots t_k) = 1 + \sum_{i=1}^k \#t_i.$$

The preorder \leq_\perp is defined on $\lambda\perp$ -terms as the $\lambda\perp$ -contextual closure of $\perp \leq M$. It is easy to check that, for all $t \in \text{NF}_{\beta\perp}$, this definition and Definition 1.12 coincide.

The set of all finite approximants of the Böhm tree of M can be obtained by calculating the direct approximants of all λ -terms β -convertible with M .

Definition 1.15. Let $M \in \Lambda_\perp$.

(1) The *direct approximant* of M , written $\text{da}(M)$, is the $\lambda\perp$ -term defined as:

- $\text{da}(M) = \perp$ if $M = \lambda x_1 \dots x_k.\perp.M_1 \dots M_k$,
- $\text{da}(M) = \perp$ if $M = \lambda x_1 \dots x_k.(\lambda y.M')NM_1 \dots M_k$,
- $\text{da}(M) = \lambda x_1 \dots x_n.x_i.\text{da}(M_1) \dots \text{da}(M_k)$ if $M = \lambda x_1 \dots x_n.x_i.M_1 \dots M_k$,

(2) The *set of finite approximants of M* is defined by:

$$\text{BT}^*(M) = \{\text{da}(M') \mid M =_\beta M'\}.$$

As shown in [2, §2.3], the set $\text{BT}^*(M)$ is directed with respect to \leq_\perp . For $M \in \Lambda$, a finite approximant $t \in \text{NF}_{\beta\perp}$ belongs to $\text{BT}^*(M)$ exactly when $t \leq_\perp \text{BT}(M)$, therefore $\text{BT}(M) = \bigvee \text{BT}^*(M)$. Moreover, the following syntactic continuity property holds.

Lemma 1.16. Let $M \in \Lambda_\perp$ and let $C[-]$ be a $\lambda\perp$ -context. If $M = C[(\lambda x.P)Q]$ then $\text{BT}^*(C[\perp]) \subseteq \text{BT}^*(M)$.

Proof. Assume that $t \in \text{BT}^*(C[\perp])$. By definition, there exists $C'[-]$ such that $C[\perp] =_\beta C'[\perp]$ and $t = \text{da}(C'[\perp])$. Then $C[(\lambda x.P)Q] =_\beta C'[(\lambda x.P)Q]$ and $t = \text{da}(C'[(\lambda x.P)Q])$, which implies that $t \in \text{BT}^*(M)$. \square

1.6. Inequational and Lambda Theories. Inequational theories and λ -theories become the main object of study when considering the computational equivalence more important than the process of computation.

Definition 1.17. An *inequational theory* is any context closed preorder on Λ containing the β -conversion. A λ -*theory* is any context closed equivalence on Λ containing the β -conversion.

Given an inequational theory \mathcal{T} we write $M \sqsubseteq_{\mathcal{T}} N$ or $\mathcal{T} \vdash M \sqsubseteq N$ for $(M, N) \in \mathcal{T}$. Similarly, given a λ -theory \mathcal{T} , we write $M =_{\mathcal{T}} N$ or $\mathcal{T} \vdash M = N$ whenever $(M, N) \in \mathcal{T}$.

The set of all λ -theories, ordered by set theoretical inclusion, forms a complete lattice $\lambda\mathcal{T}$ that has a rich mathematical structure, as shown by Salibra and his coauthors in their works [73, 58, 63].

Definition 1.18. A λ -theory (or an inequational theory) is called:

- *consistent* if it does not equate all λ -terms;
- *extensional* if it contains the η -conversion;
- *sensible* if it equates all unsolvables.

We denote by λ the least λ -theory, by $\lambda\eta$ the least extensional λ -theory, by \mathcal{H} the least sensible λ -theory, and by \mathcal{B} the (sensible) λ -theory equating all λ -terms having the same Böhm tree. Given a λ -theory \mathcal{T} , we write $\mathcal{T}\eta$ for the least λ -theory containing $\mathcal{T} \cup \lambda\eta$.

Inequational theories are less ubiquitously studied in the literature, except when they capture some observational preorder as explained in the next section. However, they have been studied in full generality in connection with denotational models (see, e.g., [10]).

2. THE LAMBDA THEORIES \mathcal{H}^+ AND \mathcal{H}^*

Several interesting λ -theories are obtained via suitable observational preorders defined with respect to a set \mathcal{O} of *observables*. This has been first done by Morris's in his PhD thesis [64].

Definition 2.1. Let \mathcal{O} be a non-empty subset of Λ .

- The \mathcal{O} -*observational preorder* is given by:

$$M \sqsubseteq^{\mathcal{O}} N \iff \forall C[-] . C[M] \in_{\beta} \mathcal{O} \text{ entails } C[N] \in_{\beta} \mathcal{O}.$$

where $M \in_{\beta} \mathcal{O}$ means that there exists a λ -term M' such that $M \rightarrow_{\beta} M' \in \mathcal{O}$.

- The \mathcal{O} -*observational equivalence* $M \equiv^{\mathcal{O}} N$ is defined as $M \sqsubseteq^{\mathcal{O}} N$ and $N \sqsubseteq^{\mathcal{O}} M$.

By [6, Prop. 16.4.6], the relations $\sqsubseteq^{\mathcal{O}}$ and $\equiv^{\mathcal{O}}$ defined above are actually inequational and λ -theories. In the rest of the section we will discuss the λ -theories \mathcal{H}^* and \mathcal{H}^+ generated as observational equivalences by considering as observables the head normal forms and the β -normal forms, respectively, and the corresponding preorders. In both cases we also recall the characterizations given in terms of extensional equivalences on Böhm-trees.

2.1. \mathcal{H}^* : Böhm Trees and Infinite η -Expansions. The λ -theory \mathcal{H}^* has been defined by Wadsworth and Hyland as an observational equivalence in [81, 46], where they proved that it corresponds to the equational theory induced by Scott's model \mathcal{D}_{∞} . In the years, \mathcal{H}^* has become the most well studied λ -theory [6, 43, 40, 71, 60, 15].

Definition 2.2. We let $\sqsubseteq_{\mathcal{H}^*}$ be the \mathcal{O} -observational preorder obtained by taking as \mathcal{O} the set of head normal forms and \mathcal{H}^* be the corresponding equivalence.

Notice that $M =_{\mathcal{H}^*} N$ is equivalent to say that M, N are not semi-separable. It is easy to check that \mathcal{H}^* is an extensional λ -theory. A first characterization of \mathcal{H}^* can be given in terms of maximal consistent extension (also known as *Post-completion*) of \mathcal{H} , and such a maximality property extends to the corresponding inequational theory. The following lemma is a generalization of [6, Thm. 16.2.6] that encompasses the inequational case.

Lemma 2.3. The preorder $\sqsubseteq_{\mathcal{H}^*}$ and the equivalence \mathcal{H}^* are maximal among consistent sensible inequational theories and λ -theories, respectively.

Proof. Let $\sqsubseteq_{\mathcal{T}}$ be an inequational theory such that $\sqsubseteq_{\mathcal{H}^*} \subsetneq \sqsubseteq_{\mathcal{T}}$. This means that there exist M, N such that $M \sqsubseteq_{\mathcal{T}} N$ while $M \not\sqsubseteq_{\mathcal{H}^*} N$. By Definition 2.2, there is a context $C[-]$ such that $C[M]$ has an hnf while $C[N]$ does not. By Theorem 1.8, there is a head context $H[-] = (\lambda \vec{x}.[-])\vec{P}$ such that $H[C[M]] =_{\beta} \mathbf{I}$ and $H[C[N]]$ is unsolvable. As $M \sqsubseteq_{\mathcal{T}} N$ we get:

$$\mathbf{I} =_{\beta} H[C[M]] \sqsubseteq_{\mathcal{T}} H[C[N]] =_{\mathcal{T}} \Omega_3 \quad \text{for } \Omega_3 = \Delta_3 \Delta_3 \text{ and } \Delta_3 = \lambda x. xxx.$$

The rightmost equality $=_{\mathcal{T}}$ holds because Ω_3 is unsolvable and the $\sqsubseteq_{\mathcal{T}}$ is sensible. Since $\Omega_3 \sqsubseteq_{\mathcal{H}^*} \mathbf{I}$ and $\sqsubseteq_{\mathcal{H}^*} \subseteq \sqsubseteq_{\mathcal{T}}$, we obtain $\Omega_3 =_{\mathcal{T}} \mathbf{I}$ which leads to:

$$\mathbf{I} =_{\mathcal{T}} \Omega_3 =_{\beta} \Omega_3 \Delta_3 =_{\mathcal{T}} \mathbf{I} \Delta_3 =_{\beta} \Delta_3.$$

Since \mathbf{I} and Δ_3 are $\beta\eta$ -distinct normal form, this contradicts the Böhm Theorem [13]. \square

The characterization of \mathcal{H}^* in terms of trees requires the notion of “infinite η -expansion” of a Böhm-like tree. Intuitively, the Böhm-like tree V is an infinite η -expansion of U , if it is obtained from U by performing countably many possibly infinite η -expansions. The classic definition is given in terms of tree extensions [6, Def. 10.2.10]; here we proceed coinductively.

Definition 2.4. Given two Böhm-like trees U and V , we say that V is a (possibly) *infinite η -expansion* of U , written $U \leq_{\infty}^{\eta} V$, if either $U = V = \perp$, or (for some $i, k, m, n \geq 0$):

$$U = \lambda x_1 \dots x_n. x_i U_1 \dots U_k \quad \text{and} \quad V = \lambda x_1 \dots x_n z_1 \dots z_m. x_i V_1 \dots V_k V'_1 \dots V'_m$$

where $z \notin \text{FV}(x_i U_1 \dots U_k)$, $U_j \leq_{\infty}^{\eta} V_j$ for all $j \leq k$ and $z_{\ell} \leq_{\infty}^{\eta} V'_{\ell}$ for all $\ell \leq m$.

Notice that in Barendregt's book [6, Def. 10.2.10(iii)], the relation above is denoted by \leq_{η} . We prefer to use a different notation because we want to emphasize the possibly infinitary nature of such η -expansions.

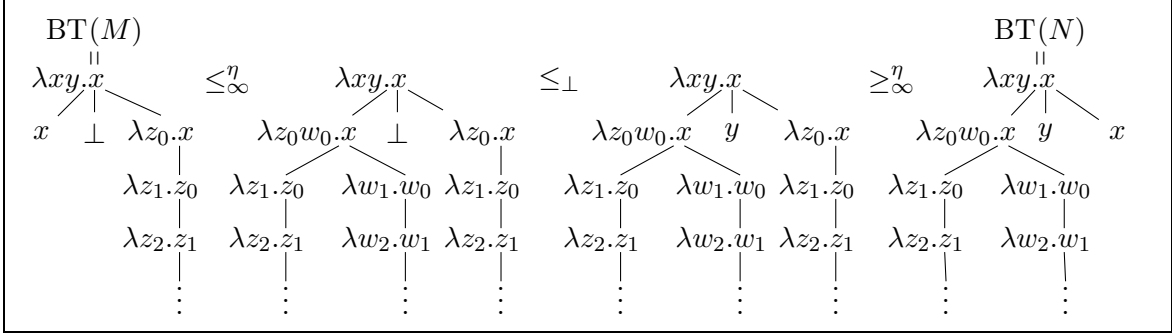


Figure 2: A situation witnessing the fact that $M \sqsubseteq_{\mathcal{H}^*} N$ holds.

Theorem 2.5. [6, Thm. 19.2.9] Let $M, N \in \Lambda$.

- (i) $M \sqsubseteq_{\mathcal{H}^*} N$ if and only if there are Böhm-like trees U, V such that $BT(M) \leq_\infty^\eta U \leq_\perp V \geq_\infty^\eta BT(N)$.
- (ii) $M =_{\mathcal{H}^*} N$ if and only if there is a Böhm-like tree U such that $BT(M) \leq_\infty^\eta U \geq_\infty^\eta BT(N)$.

In other words, \mathcal{H}^* equates all λ -terms whose Böhm trees are equal up to countably many (possibly) infinite η -expansions. From Theorem 1.11, it follows that the trees U, V appearing in the statements above can always be chosen λ -definable (see [6, Ex. 10.6.7]).

Example 2.6.

- (1) The typical example is $\mathbf{I} =_{\mathcal{H}^*} \mathbf{J}$, since clearly $BT(\mathbf{J})$ is an infinite η -expansion of \mathbf{I} , so $BT(\mathbf{I}) \leq_\infty^\eta BT(\mathbf{J})$ holds.
- (2) As a consequence, we get that $BT([\mathbf{I}]_{n \in \mathbb{N}}) \leq_\infty^\eta BT([\mathbf{J}]_{n \in \mathbb{N}})$ for $[\mathbf{I}]_{n \in \mathbb{N}} = [\mathbf{I}, [\mathbf{I}, [\mathbf{I}, \dots]]]$ and $[\mathbf{J}]_{n \in \mathbb{N}} = [\mathbf{J}, [\mathbf{J}, [\mathbf{J}, \dots]]]$.
- (3) For $M = \lambda xy.xx\Omega(\mathbf{J}x)$ and $N = \lambda xy.x(\lambda z_0w_0.x(\mathbf{J}z_0)(\mathbf{J}w_0))yx$, we have $M \sqsubseteq_{\mathcal{H}^*} N$ (as shown in Figure 2) but $M \neq_{\mathcal{H}^*} N$. As we will see in Section 2.2, it is possible to represent the subterm $\lambda z_0w_0.x(\mathbf{J}z_0)(\mathbf{J}w_0)$ as $\mathbf{J}_T x$, where \mathbf{J}_T is an infinite η -expansion of \mathbf{I} following a suitable tree T .

The point (2) shows that for proving $BT(M) \leq_\infty^\eta BT(N)$ one may need to perform denumerably many infinite η -expansions. Point (3) shows that for proving $M \sqsubseteq_{\mathcal{H}^*} N$, it may not be enough to infinitely η -expand $BT(M)$ to match the structure of $BT(N)$: one may need to perform infinite η -expansions on both sides and cut some subtrees of $BT(N)$.

Remark 2.7. From Theorem 2.5 and Definition 2.4 it follows that if $M \sqsubseteq_{\mathcal{H}^*} N$ and M solvable then also N is solvable and M, N have similar hnfs.

2.2. The Infinite η -Expansion \mathbf{J}_T . Wadsworth's combinator \mathbf{J} is the typical example of an infinite η -expansion of the identity. However, there are many λ -terms M that satisfy the property of being infinite η -expansions of the identity, namely $BT(\mathbf{I}) \leq_\infty^\eta BT(M)$.

Recall from Section 1.5 that $\lfloor BT(M) \rfloor$ denotes the underlying tree of $BT(M)$.

Definition 2.8. Let $M \in \Lambda$ and $T \in \mathbb{T}^\infty$. We say that M is an *infinite η -expansion of the identity following T* whenever $BT(\mathbf{I}) \leq_\infty^\eta BT(M)$ and $\lfloor BT(M) \rfloor = T$.

For instance, \mathbf{J} follows the infinite unary tree T corresponding to the map $T(\sigma) = 1$ for all $\sigma = \langle 0, \dots, 0 \rangle$. We now provide a characterization of all such infinite η -expansions.

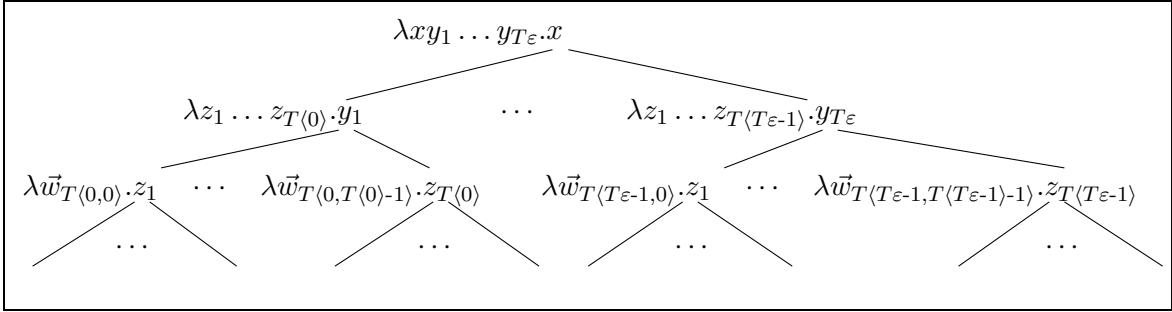


Figure 3: The Böhm-like tree of an infinite η -expansion of \mathbf{I} following $T \in \mathbb{T}_{\text{rec}}^\infty$. To lighten the notations we write $T\sigma$ rather than $T(\sigma)$ and we let $\vec{w}_n := w_1, \dots, w_n$.

Proposition 2.9. For all $T \in \mathbb{T}^\infty$, there exists a λ -term \mathbf{J}_T which is an infinite η -expansion of the identity following T if and only if T is recursive.

Proof. (\Rightarrow) By Theorem 1.11, $\text{BT}(\mathbf{J}_T)$ is partial recursive and so is its underlying tree T . Since $\text{BT}(\mathbf{I}) \leq_\infty^\eta \text{BT}(\mathbf{J}_T)$, $\text{BT}(\mathbf{J}_T)$ cannot have any occurrences of \perp so $\text{dom}(T)$ is decidable.

(\Leftarrow) We fix a bijective encoding of all finite sequences of natural numbers $\# : \mathbb{N}^{<\omega} \rightarrow \mathbb{N}$ which is *effective* in the sense that the code $\#(\sigma.n)$ is computable from $\#\sigma$ and n . We write $\lceil \sigma \rceil$ for the corresponding Church numeral $\mathbf{c}_{\#\sigma}$. Using a fixed point combinator \mathbf{Y} , we define a λ -term $X \in \Lambda^o$ satisfying the following recursive equation (for all $\sigma \in \text{dom}(T)$):

$$X[\sigma] =_\beta \lambda x z_1 \dots z_m. x(X[\sigma.0]z_1) \cdots (X[\sigma.m-1]z_m) \text{ where } m = T(\sigma). \quad (2.1)$$

(The existence of such a λ -term follows from the fact that T is recursive, the effectiveness of the encoding $\#$ and Church's Thesis.) We prove by coinduction that for all $\sigma \in \text{dom}(T)$, $X[\sigma]$ is an infinite η -expansion of the identity following $T \upharpoonright_\sigma$. Indeed, $X[\sigma]$ is β -convertible to the λ -term of Equation 2.1. By coinductive hypothesis we get for all $i < T(\sigma)$ that $\mathbf{I} \leq_\infty^\eta X[\sigma.i]$ and $\lceil \text{BT}(X[\sigma.i]) \rceil = T \upharpoonright_{\sigma.i}$. From this, it follows that $z_i =_\beta \mathbf{I}z_i \leq_\infty^\eta X[\sigma.i]z_i$ and the underlying tree remains unchanged $\lceil \text{BT}(X[\sigma.i]z_i) \rceil = T_{\sigma.i}$. As a consequence, we conclude that $\mathbf{I} \leq_\infty^\eta X[\sigma]$ and the underlying tree of $\text{BT}(X[\sigma])$ is T . Therefore, the λ -term \mathbf{J}_T we are looking for is $X[\varepsilon]$. \square

2.3. \mathcal{H}^+ : Böhm Trees and Their Finitary η -Expansions. Perhaps surprisingly, it turns out that \mathcal{H}^* is not the first λ -theory that has been defined in terms of contextual equivalence. Indeed, Morris's original extensional observational equivalence is the following.

Definition 2.10. *Morris's inequational theory* $\sqsubseteq_{\mathcal{H}^+}$ is the \mathcal{O} -observational preorder obtained by taking as \mathcal{O} the set NF_β of β -normal forms. We denote by \mathcal{H}^+ the corresponding equivalence, which we call *Morris's λ -theory*².

Notice that it is equivalent to take as observables the $\beta\eta$ -normal forms, since $M \rightarrow_\beta \text{nf}_\beta(M)$ exactly when $M \rightarrow_{\beta\eta} \text{nf}_{\beta\eta}(M)$. Thus \mathcal{H}^+ is an extensional λ -theory as well. It is easy to show that $M \sqsubseteq_{\mathcal{H}^+} N$ entails $M \sqsubseteq_{\mathcal{H}^*} N$, therefore we have $\mathcal{H}^+ \subsetneq \mathcal{H}^*$. In [25], Coppo, Dezani-Ciancaglini and Zacchi defined a filter model having \mathcal{H}^+ as equational theory. Also \mathcal{H}^+ can be characterized via a suitable extensional equivalence between Böhm trees.

² The notation \mathcal{H}^+ for Morris's λ -theory has been used in [62, 17, 50]. The same λ -theory is denoted \mathcal{T}_{NF} in Barendregt's book [6] and \mathbf{N} in Paolini and Ronchi della Rocca's one [71].

Intuitively, the Böhm-like tree U is a finitary η -expansion of V , if it is obtained from V by performing countably many finite η -expansions.

Definition 2.11. Given two Böhm-like trees U and V , we say that V is a *finitary η -expansion* of U , written $U \leq^\eta V$ if either $U = V = \perp$, or (for some $i, k, m, n \geq 0$):

$$U = \lambda x_1 \dots x_n. x_i U_1 \dots U_k \quad \text{and} \quad V = \lambda x_1 \dots x_n z_1 \dots z_m. x_i V_1 \dots V_k Q_1 \dots Q_m$$

where $\vec{z} \notin \text{FV}(x_i U_1 \dots U_k)$, $U_j \leq^\eta V_j$ for all $j \leq k$ and $\vec{Q} \in \Lambda \cap \text{NF}_\beta$ are such that $Q_\ell \twoheadrightarrow_\eta z_\ell$ for all $\ell \leq m$.

Two λ -terms M, N are equivalent in \mathcal{H}^+ exactly when their Böhm trees are equal up to countably many η -expansions of finite depth.

Theorem 2.12. [45, Thm. 2.6] For $M, N \in \Lambda$, we have that $M =_{\mathcal{H}^+} N$ if and only if there exists a Böhm-like tree U such that $\text{BT}(M) \leq^\eta U \geq^\eta \text{BT}(N)$.

Example 2.13. Recall from Example 2.6(2) that $[\mathbf{I}]_{n \in \mathbb{N}} = [\mathbf{I}, [\mathbf{I}, [\mathbf{I}, \dots]]]$ and define the sequence $[\mathbf{1}_n]_{n \in \mathbb{N}} = [\mathbf{I}, [\mathbf{1}_1, [\mathbf{1}_2, \dots]]]$ where $\mathbf{1}_n$ is defined on Page 7. From Definition 2.11 it follows $\text{BT}([\mathbf{I}]_{n \in \mathbb{N}}) \leq^\eta \text{BT}([\mathbf{1}_n]_{n \in \mathbb{N}})$ while, for instance, $\text{BT}([\mathbf{I}]_{n \in \mathbb{N}}) \not\leq^\eta \text{BT}([\mathbf{J}]_{n \in \mathbb{N}})$.

As a brief digression, notice that the λ -terms $[\mathbf{I}]_{n \in \mathbb{N}}$ and $[\mathbf{1}_n]_{n \in \mathbb{N}}$ can be used to show that $\mathcal{B}\eta \subsetneq \mathcal{H}^+$. Indeed, for $M, N \in \Lambda$, $M \rightarrow_\eta N$ entails that $\text{BT}(M)$ can be obtained from $\text{BT}(N)$ by performing at most *one* η -expansion at every position (see [6, Lemma 16.4.3]). However, to equate the Böhm trees of $[\mathbf{I}]_{n \in \mathbb{N}}$ and $[\mathbf{1}_n]_{n \in \mathbb{N}}$, at every level one needs to perform η -expansions of increasing depth and this is impossible in $\mathcal{B}\eta$ (as shown in [50]).

As shown in [17] by exploiting a revised Böhm-out technique, the following weak separation result holds. (For the interested reader a fully detailed proof will appear in [49].)

Theorem 2.14 (Morris Separation). Let $M, N \in \Lambda$ such that $M \sqsubseteq_{\mathcal{H}^*} N$ while $M \not\sqsubseteq_{\mathcal{H}^+} N$. There exists a context $C[-]$ such that $C[M] =_{\beta\eta} \mathbf{I}$ and $C[N] =_{\mathcal{B}} \mathbf{J}_T$ for some $T \in \mathbb{T}_{\text{rec}}^\infty$.

This allows to weakly separate also λ -terms like \mathbf{I} and \mathbf{J} that are not semi-separable.

2.4. Extensional Approximants. As far as we know, in the literature there is no characterization of $\sqsubseteq_{\mathcal{H}^+}$ in terms of extensional equality between Böhm trees. However, Lévy in [55] provides a characterization in terms of “extensional approximants” of Böhm trees. Recall from Definition 1.15(2) that $\text{BT}^*(M)$ is the set of all finite approximants of $\text{BT}(M)$.

Definition 2.15. For $M \in \Lambda$, the set $\text{BT}^e(M)$ of all *extensional (finite) approximants* of $\text{BT}(M)$ is defined as follows:

$$\text{BT}^e(M) = \{\text{nf}_\eta(t) \mid t \in \text{BT}^*(M'), M' \twoheadrightarrow_\eta M\}.$$

Example 2.16. The sets of extensional approximants of some notable λ -terms:

- $\text{BT}^e(\mathbf{I}) = \{\perp, \mathbf{I}, \lambda x z_0. x \perp, \lambda x z_0. x (\lambda z_1. z_0 \perp), \lambda x z_0. x (\lambda z_1. z_0 (\lambda z_2. z_1 \perp)), \dots\}$,
- $\text{BT}^e(\mathbf{J}) = \text{BT}^e(\mathbf{I}) - \{\mathbf{I}\}$.

(Here we decided to display those approximants having a regular shape, but also $\lambda\perp$ -terms like $\lambda x z_0 z_1 z_2. x (\lambda w_0 w_1. z_0 w_0 \perp) z_1 \perp$ belong to these sets).

The following result is taken from [55] and will be used in the proof of Corollary 4.17.

Theorem 2.17. For $M, N \in \Lambda$ we have $M \sqsubseteq_{\mathcal{H}^+} N$ if and only if $\text{BT}^e(M) \subseteq \text{BT}^e(N)$.

3. THE RELATIONAL GRAPH MODELS

In this section we recall the definition of a *relational graph model* (rgm, for short). Individual examples of has been previously studied in the literature as models of the λ -calculus [19, 60, 28, 48], of nondeterministic λ -calculi [20] and of resource calculi [61, 65]. However, the class of relational graph models was formally introduced in [62].

3.1. The Relational Semantics. Relational graph models are called *relational* since they are reflexive objects in the Cartesian closed category \mathbf{MRel} [19], which is the Kleisli category of \mathbf{Rel} with respect to the finite multisets comonad $\mathcal{M}_f(-)$. Since we do not use the underlying symmetric monoidal category, we present directly its Cartesian closed structure. Recall that the definitions and notations concerning multisets have been introduced in Subsection 1.1.

Definition 3.1. The category \mathbf{MRel} is defined as follows:

- The objects of \mathbf{MRel} are all the sets.
- A morphism from A to B is a relation from $\mathcal{M}_f(A)$ to B ; in other words, $\mathbf{MRel}(A, B) = \mathcal{P}(\mathcal{M}_f(A) \times B)$.
- The identity of A is the relation $\text{Id}_A = \{([\alpha], \alpha) \mid \alpha \in A\} \in \mathbf{MRel}(A, A)$.
- The composition of $f \in \mathbf{MRel}(A, B)$ and $g \in \mathbf{MRel}(B, C)$ is defined by:

$$g \circ f = \left\{ (a, \gamma) \mid \begin{array}{l} \exists k \in \mathbb{N}, \exists (a_1, \beta_1), \dots, (a_k, \beta_k) \in f \text{ such that} \\ a = a_1 + \dots + a_k \text{ and } ([\beta_1, \dots, \beta_k], \gamma) \in g \end{array} \right\}.$$

Given two sets A_1, A_2 , we denote by $A_1 \& A_2$ their disjoint union $(\{1\} \times A_1) \cup (\{2\} \times A_2)$. Hereafter we adopt the following convention.

Convention. We consider the canonical bijection (also known as *Seely isomorphism* [12]) between $\mathcal{M}_f(A_1) \times \mathcal{M}_f(A_2)$ and $\mathcal{M}_f(A_1 \& A_2)$ as an equality. As a consequence, we still denote by (a_1, a_2) the corresponding element of $\mathcal{M}_f(A_1 \& A_2)$.

Theorem 3.2. The category \mathbf{MRel} is a Cartesian closed category.

Proof. The terminal object \top is the empty set \emptyset , and the unique element of $\mathbf{MRel}(A, \emptyset)$ is the empty relation.

Given two sets A_1 and A_2 , their categorical product in \mathbf{MRel} is their disjoint union $A_1 \& A_2$ and the projections π_1, π_2 are given by:

$$\pi_i = \{([(i, a)], a) \mid a \in A_i\} \in \mathbf{MRel}(A_1 \& A_2, A_i), \text{ for } i = 1, 2.$$

It is easy to check that this is actually the categorical product of A_1 and A_2 in \mathbf{MRel} ; given $f \in \mathbf{MRel}(B, A_1)$ and $g \in \mathbf{MRel}(B, A_2)$, the corresponding morphism $\langle f, g \rangle \in \mathbf{MRel}(B, A_1 \& A_2)$ is given by:

$$\langle f, g \rangle = \{(b, (1, \alpha)) \mid (b, \alpha) \in f\} \cup \{(b, (2, \alpha)) \mid (b, \alpha) \in g\}.$$

Given two objects A and B , the exponential object $A \Rightarrow B$ is $\mathcal{M}_f(A) \times B$ and the evaluation morphism is given by:

$$\text{ev}_{AB} = \{([(a, \beta)], a, \beta) \mid a \in \mathcal{M}_f(A) \text{ and } \beta \in B\} \in \mathbf{MRel}((A \Rightarrow B) \& A, B).$$

Again, it is easy to check that in this way we defined an exponentiation. Indeed, given any set C and any morphism $f \in \mathbf{MRel}(C \& A, B)$, there is exactly one morphism $\Lambda(f) \in \mathbf{MRel}(C, A \Rightarrow B)$ such that:

$$\text{ev}_{AB} \circ (\Lambda(f) \times \text{Id}_S) = f.$$

which is $\Lambda(f) = \{(c, (a, \beta)) \mid ((c, a), \beta) \in f\}$. \square

The category **MRel** provides a simple example of a non-well-pointed category.

Theorem 3.3. No object $A \neq \top$ is well-pointed, so neither is **MRel**.

Proof. For every $A \neq \emptyset$, we can always find $f, g : A \rightarrow A$ such that $f \neq g$ and, for all $h : \top \rightarrow A$, $f \circ h = g \circ h$. Indeed, by definition of composition, $f \circ h = \{(\omega, \alpha) \mid \exists \beta_1, \dots, \beta_k \in A, (\omega, \beta_i) \in h, ([\beta_1, \dots, \beta_k], \alpha) \in f\}$, and similarly for $g \circ h$. Hence it is sufficient to choose $f = \{(a_1, \alpha)\}$ and $g = \{(a_2, \alpha)\}$ for a_1, a_2 different multisets with the same support. \square

3.2. The Class of Relational Graph Models. The class of graph models constitutes a subclass of the continuous semantics [75] and is the simplest generalization of the Engeler and Plotkin's construction [38, 68]. This class has been widely studied in the literature and has been used to prove several interesting results [9]. We recall that a graph model is given by a set A and a total injection $i : \mathcal{P}_f(A) \times A \rightarrow A$, and induces $\mathcal{P}(A)$ as a reflexive object in the category of Scott's domains and continuous functions. Therefore, a bijective i does not induce automatically an isomorphism between $\mathcal{P}(A)$ and $\mathcal{P}(A) \Rightarrow \mathcal{P}(A)$. As shown in [9, §5.5], no graph model \mathcal{G} can be extensional because $\mathcal{G} \models \mathbf{1} \sqsubseteq \mathbf{I}$ is never satisfied.

The definition of a relational graph model mimics the one of a graph model while replacing finite sets with finite multisets. As we will see, relational graph models capture a particular subclass of reflexive objects living in **MRel**.

Definition 3.4. A *relational graph model* $\mathcal{D} = (D, i)$ is given by an infinite set D and a total injection $i : \mathcal{M}_f(D) \times D \rightarrow D$. We say that \mathcal{D} is *extensional* when i is bijective.

Intuitively, $i(a, \alpha) = \beta$ indicates that the “arrow type” $a \rightarrow \alpha$ is equivalent to the type β . In particular, in an extensional relational graph model, every element of the model can be seen as an arrow. Keeping this intuition in mind, we adopt the notation below.

Notation 3.5. Given an rgm $\mathcal{D} = (D, i)$, $a \in \mathcal{M}_f(D)$ and $\alpha \in D$, we write $a \rightarrow_i \alpha$ (or simply $a \rightarrow \alpha$, when i is clear) as an alternative notation for $i(a, \alpha)$.

As shown in the next proposition, the reflexive object induced by a relational graph model (D, i) is not some powerset of D as in the case of regular graph models, but rather D itself. This opens the way to define extensional reflexive objects.

Proposition 3.6. Given an rgm $\mathcal{D} = (D, i)$ we have that:

- (i) \mathcal{D} induces a reflexive object (D, App, λ) where

$$\lambda = \{([(a, \alpha)], a \rightarrow_i \alpha) \mid a \in \mathcal{M}_f(D), \alpha \in D\} \in \mathbf{MRel}(D \Rightarrow D, D),$$

$$\text{App} = \{([a \rightarrow_i \alpha], (a, \alpha)) \mid a \in \mathcal{M}_f(D), \alpha \in D\} \in \mathbf{MRel}(D, D \Rightarrow D),$$

- (ii) If moreover \mathcal{D} is extensional, then also the induced reflexive object is.

Proof. (i) $\text{App} \circ \lambda = \{([(a, \alpha)], (a, \alpha)) \mid ([(a, \alpha)], a \rightarrow \alpha) \in \lambda, ([a \rightarrow \alpha], (a, \alpha)) \in \text{App}\} = \{([(a, \alpha)], (a, \alpha)) \mid a \in \mathcal{M}_f(D), \alpha \in D\} = \text{Id}_{\mathcal{M}_f(D) \times D} = \text{Id}_{D \Rightarrow D}$.

(ii) If i is bijective for every $\beta \in D$ we have $\beta = a \rightarrow_i \alpha$ for some $a \in \mathcal{M}_f(D)$ and $\alpha \in D$. So $\lambda \circ \text{App} = \{([a \rightarrow \alpha], a \rightarrow \alpha) \mid ([a \rightarrow \alpha], (a, \alpha)) \in \text{App}, ([(a, \alpha)], a \rightarrow \alpha) \in \lambda\} = \{([a \rightarrow \alpha], a \rightarrow \alpha) \mid a \in \mathcal{M}_f(D), \alpha \in D\} = \{([\beta], \beta) \mid \beta \in D\} = \text{Id}_D$. \square

Note that, when i is just injective, there are in principle different morphisms that could be chosen as inverses of λ . Therefore, there exist reflexive objects in \mathbf{MRel} that are not relational graph models. However, since every isomorphism $f \in \mathbf{MRel}(A, A)$ is of the form $f = \{([\alpha], i(\alpha)) \mid \alpha \in A\}$ for some bijective map i , the class of extensional relational graph models coincides with the one of extensional reflexive objects living in this category.

3.3. Building Relational Graph Models by Completion. Relational graph models – just like the regular ones – can be built by performing the free completion of a partial pair.

Definition 3.7.

- (1) A *partial pair* \mathcal{A} is a pair (A, j) where A is a non-empty set of elements (called *atoms*) and $j : \mathcal{M}_f(A) \times A \rightarrow A$ is a partial injection.
- (2) A partial pair \mathcal{A} is called *extensional* when j is a bijection between $\text{dom}(j)$ and A .
- (3) A partial pair \mathcal{A} is called *total* when j is a total function, and in this case \mathcal{A} is a relational graph model.

Hereafter, we will only consider partial pairs \mathcal{A} whose underlying set A does not contain any pair. This is not restrictive because partial pairs can be considered up to isomorphism.

Definition 3.8. The *free completion* $\overline{\mathcal{A}}$ of a partial pair \mathcal{A} is the pair $(\overline{A}, \overline{j})$ defined as: $\overline{A} = \bigcup_{n \in \mathbb{N}} A_n$, where $A_0 = A$ and $A_{n+1} = ((\mathcal{M}_f(A_n) \times A_n) - \text{dom}(j)) \cup A$; moreover

$$\overline{j}(a, \alpha) = \begin{cases} j(a, \alpha) & \text{if } (a, \alpha) \in \text{dom}(j), \\ (a, \alpha) & \text{otherwise.} \end{cases}$$

It is well known for graph models, and easy to check for relational graph models, that every \mathcal{D} is isomorphic to its own free completion $\overline{\mathcal{D}} \cong \mathcal{D}$. In particular, given a partial pair \mathcal{A} , we have that $\overline{\overline{\mathcal{A}}} \cong \overline{\mathcal{A}}$.

Proposition 3.9. If \mathcal{A} is an (extensional) partial pair, then $\overline{\mathcal{A}}$ is an (extensional) rgm.

Proof. The proof of the fact that $\overline{\mathcal{A}}$ is an rgm is analogous to the one for regular graph models [9]. It is easy to check that when j is bijective, also its completion \overline{j} is. \square

The following relational graph models are built by free completion and will be running examples in the next sections.

Example 3.10. Some examples of relational graph model:

- $\mathcal{E} = (\overline{\mathbb{N}}, \emptyset)$ was introduced in [48],
- $\mathcal{D}_\omega = (\{\star\}, \{(\omega, \star) \mapsto \star\})$ was first defined (up to isomorphism) in [19],
- $\mathcal{D}_\star = (\{\star\}, \{([\star], \star) \mapsto \star\})$ was introduced in [62].

Notice that \mathcal{D}_ω and \mathcal{D}_\star are extensional, while \mathcal{E} is not.

3.4. Categorical Interpretation. We now show how λ -terms and Böhm trees can be interpreted in a relational graph model, and we review their main properties.

Recall that notions and notation concerning multisets have been introduced in Section 1.1. Given two n -uples $\vec{a}, \vec{b} \in \mathcal{M}_f(A)^n$ we write $\vec{a} + \vec{b}$ for $(a_1 + b_1, \dots, a_n + b_n) \in \mathcal{M}_f(A)^n$.

Definition 3.11. Let \mathcal{D} be an rgm, $M \in \Lambda$ and $\text{FV}(M) \subseteq \{x_1, \dots, x_n\}$. The *categorical interpretation* of M in \mathcal{D} w.r.t. \vec{x} is the relation $|M|_{\vec{x}}^{\mathcal{D}} \subseteq \mathcal{M}_f(D)^n \times D$ defined by:

- i. $|x_i|_{\vec{x}}^{\mathcal{D}} = \{((\omega, \dots, \omega, [\alpha], \omega, \dots, \omega), \alpha) \mid \alpha \in D\}$, where $[\alpha]$ stands in i -th position.
- ii. $|\lambda y.N|_{\vec{x}}^{\mathcal{D}} = \{(\vec{a}, a \rightarrow_i \alpha) \mid ((\vec{a}, a), \alpha) \in |N|_{\vec{x},y}^{\mathcal{D}}\}$ where we take $y \notin \vec{x}$ by α -conversion.
- iii. $|PQ|_{\vec{x}}^{\mathcal{D}} = \{((\vec{a}_0 + \dots + \vec{a}_k), \alpha) \mid \exists \alpha_1, \dots, \alpha_k \in \mathcal{D} \text{ such that } (\vec{a}_0, [\alpha_1, \dots, \alpha_k] \rightarrow_i \alpha) \in |P|_{\vec{x}}^{\mathcal{D}} \text{ and } (\vec{a}_j, \alpha_j) \in |Q|_{\vec{x}}^{\mathcal{D}} \text{ for all } 1 \leq j \leq k\}$.

This definition extends to $\lambda\perp$ -terms M by setting $|\perp|_{\vec{x}}^{\mathcal{D}} = \emptyset$ and to Böhm trees of λ -terms by interpreting all their finite approximants, namely by setting $|\text{BT}(M)|_{\vec{x}}^{\mathcal{D}} = \bigcup_{t \in \text{BT}^*(M)} |t|_{\vec{x}}^{\mathcal{D}}$.

It is easy to check that the definition above is an inductive characterization of the usual categorical interpretation of λ -terms as morphisms of a Cartesian closed category.

Convention. From now on, whenever we write $|M|_{\vec{x}}^{\mathcal{D}}$ we always assume that $\text{FV}(M) \subseteq \vec{x}$. When M is a closed λ -term we consider $|M|^{\mathcal{D}}$ simply as a subset of D . In all our notations we omit the model \mathcal{D} when it is clear from the context.

Example 3.12. Let \mathcal{D} be any rgm. Then we have:

- (1) $|\mathbf{I}|^{\mathcal{D}} = \{[\alpha] \rightarrow \alpha \mid \alpha \in D\}$ and
- (2) $|\mathbf{1}|^{\mathcal{D}} = \{[a \rightarrow \alpha] \rightarrow a \rightarrow \alpha \mid \alpha \in D, a \in \mathcal{M}_f(D)\}$, thus:
- (3) $|\mathbf{J}|^{\mathcal{D}} = \{[\alpha] \rightarrow \alpha \mid \alpha \in D'\} \subseteq |\mathbf{1}|^{\mathcal{D}} \subseteq |\mathbf{I}|^{\mathcal{D}}$, where D' is the smallest subset of D satisfying: if $\alpha \in D$ then $\omega \rightarrow \alpha \in D'$; if $\alpha \in D$ and $a \in \mathcal{M}_f(D')$ then $a \rightarrow \alpha \in D'$,
- (4) $|\Delta|^{\mathcal{D}} = \{(a + [a \rightarrow \alpha]) \rightarrow \alpha \mid \alpha \in D, a \in \mathcal{M}_f(D)\}$ therefore:
- (5) $|\Omega|^{\mathcal{D}} = |\perp|^{\mathcal{D}} = \emptyset$,
- (6) $|\lambda x.x\Omega|^{\mathcal{D}} = \{[\omega \rightarrow \alpha] \rightarrow \alpha \mid \alpha \in D\}$.

It follows that $|\mathbf{I}| = |\mathbf{1}|$ in both \mathcal{D}_ω and \mathcal{D}_\star , but $|\mathbf{I}|^{\mathcal{D}_\omega} = |\mathbf{J}|^{\mathcal{D}_\omega}$, while $\star \in |\mathbf{I}|^{\mathcal{D}_\star} - |\mathbf{J}|^{\mathcal{D}_\star}$.

3.5. Soundness. Relational graph models satisfy the following substitution property, and are sound models of λ -calculus.

Lemma 3.13 (Substitution). Let $M, N \in \Lambda$ and \mathcal{D} be an rgm. For $\vec{a} \in \mathcal{M}_f(D)^n$ and $\alpha \in D$ we have that $(\vec{a}, \alpha) \in |M\{N/y\}|_{\vec{x}}^{\mathcal{D}}$ if and only if there exist $b = [\beta_1, \dots, \beta_k] \in \mathcal{M}_f(D)$ and $\vec{a}_0, \dots, \vec{a}_k \in \mathcal{M}_f(D)^n$ such that $(\vec{a}_\ell, \beta_\ell) \in |N|_{\vec{x}}^{\mathcal{D}}$, for $1 \leq \ell \leq k$, $((\vec{a}_0, b), \alpha) \in |M|_{\vec{x},y}^{\mathcal{D}}$ and $\vec{a} = \sum_{\ell=0}^k \vec{a}_\ell$.

Proof. We proceed by induction on M , the only interesting case being $M = PQ$.

(\Rightarrow) We know that $(\vec{a}, \alpha) \in |M\{N/y\}|_{\vec{x}}^{\mathcal{D}}$ if and only if there are $\gamma_1, \dots, \gamma_k$ and a decomposition $\vec{a} = \sum_{\ell=0}^k \vec{a}^\ell$ such that $(\vec{a}^0, [\gamma_1, \dots, \gamma_k] \rightarrow \alpha) \in |P\{N/y\}|_{\vec{x}}^{\mathcal{D}}$ and $(\vec{a}^\ell, \gamma_\ell) \in |Q\{N/y\}|_{\vec{x}}^{\mathcal{D}}$ for $1 \leq \ell \leq k$. By applying the induction hypothesis to the former assumption, we get $b^0 = [\beta_1^0, \dots, \beta_m^0]$ and a decomposition $\vec{a}^0 = \sum_{j=0}^m \vec{a}_j^0$ such that $((\vec{a}_0^0, b^0), [\gamma_1, \dots, \gamma_k] \rightarrow \alpha) \in |P|_{\vec{x},y}^{\mathcal{D}}$ and $(\vec{a}_i^0, \beta_i^0) \in |N|_{\vec{x}}^{\mathcal{D}}$ for $1 \leq i \leq m$. From the latter, for each $\ell = 1, \dots, k$ we get $b^\ell = [\beta_1^\ell, \dots, \beta_{k_\ell}^\ell]$ and a decomposition $\vec{a}^\ell = \sum_{j=0}^{k_\ell} \vec{a}_j^\ell$ such that $((\vec{a}_0^\ell, b^\ell), \gamma_\ell) \in |Q|_{\vec{x},y}^{\mathcal{D}}$ and $(\vec{a}_j^\ell, \beta_j^\ell) \in |N|_{\vec{x}}^{\mathcal{D}}$ for $1 \leq j \leq k_\ell$. We conclude that $((\sum_{\ell=0}^k \vec{a}_0^\ell, \sum_{\ell=0}^k b^\ell), \alpha) \in |PQ|_{\vec{x},y}^{\mathcal{D}}$.

(\Leftarrow) By analogue calculations. \square

Lemma 3.14 (Monotonicity). Let \mathcal{D} be an rgm, and $M, N \in \Lambda$. If $|M|_{\vec{x}}^{\mathcal{D}} \subseteq |N|_{\vec{x}}^{\mathcal{D}}$ then for all contexts $C[-]$ we have $|C[M]|_{\vec{x}}^{\mathcal{D}} \subseteq |C[N]|_{\vec{x}}^{\mathcal{D}}$.

Proof. Notice that, by the Convention above, we assume $\text{FV}(MNC[-]) \subseteq \vec{x}$. The result follows by a straightforward induction on $C[-]$. \square

Theorem 3.15 (Soundness). Let $M, N \in \Lambda$ and \mathcal{D} be a relational graph model. If $M =_\beta N$ then $|M|_{\vec{x}}^{\mathcal{D}} = |N|_{\vec{x}}^{\mathcal{D}}$.

Proof. From the substitution lemma and Lemma 3.14 we have that $M \rightarrow_\beta M'$ entails $|M|_{\vec{x}} = |M'|_{\vec{x}}$. By Church Rosser $M =_\beta N$ if and only if they have a common reduct P such that $M \rightarrow_\beta P$ and $N \rightarrow_\beta P$. Summing up, we have $|M|_{\vec{x}} = |P|_{\vec{x}} = |N|_{\vec{x}}$. \square

Definition 3.16.

- The λ -theory induced by a relational graph model \mathcal{D} is defined by

$$\text{Th}(\mathcal{D}) = \{(M, N) \in \Lambda \times \Lambda \mid |M|_{\vec{x}} = |N|_{\vec{x}}\}.$$

We write $\mathcal{D} \models M = N$ for $(M, N) \in \text{Th}(\mathcal{D})$.

- Similarly, the *inequational theory* induced by \mathcal{D} is given by

$$\text{Th}_{\sqsubseteq}(\mathcal{D}) = \{(M, N) \in \Lambda \times \Lambda \mid |M|_{\vec{x}} \subseteq |N|_{\vec{x}}\}.$$

We write $\mathcal{D} \models M \sqsubseteq N$ for $(M, N) \in \text{Th}_{\sqsubseteq}(\mathcal{D})$.

- An rgm \mathcal{D} is called *\mathcal{O} -fully abstract* when $\mathcal{D} \models M = N$ if and only if $M \equiv^{\mathcal{O}} N$.
- \mathcal{D} is *inequationally \mathcal{O} -fully abstract* when $\mathcal{D} \models M \sqsubseteq N$ if and only if $M \sqsubseteq^{\mathcal{O}} N$.
- We say that a λ -theory (resp. inequational theory) \mathcal{T} is *representable by a relational graph model* if there exists an rgm \mathcal{D} such that $\text{Th}(\mathcal{D}) = \mathcal{T}$ (resp. $\text{Th}_{\sqsubseteq}(\mathcal{D}) = \mathcal{T}$).
- We say that a λ -theory (resp. inequational theory) is a (*resp. inequational*) *relational graph theory* if it is represented by some relational graph model.

Lemma 3.17. Let \mathcal{D} be an rgm.

- (i) If $M \rightarrow_\eta N$ then $|N|_{\vec{x}}^{\mathcal{D}} \subseteq |M|_{\vec{x}}^{\mathcal{D}}$,
- (ii) \mathcal{D} is extensional if and only if $\lambda\eta \subseteq \text{Th}(\mathcal{D})$.

Proof. (i) By inspecting their interpretations (Example 3.12(1-2)) it is clear that $|\mathbf{1}| \subseteq |\mathbf{I}|$. For all $N \in \Lambda$, $\mathcal{D} \models \mathbf{1}N \sqsubseteq \mathbf{I}N$ (monotonicity) which entails $\mathcal{D} \models \lambda x.Nx \sqsubseteq N$ (soundness).

(ii) By monotonicity $\lambda\eta \subseteq \text{Th}(\mathcal{D})$ if and only if $\mathcal{D} \models \mathbf{1} = \mathbf{I}$. As above, we know that $\mathcal{D} \models \mathbf{1} \sqsubseteq \mathbf{I}$ holds. The other inclusion holds if and only if for all $\alpha \in D$ there exist a, β such that $i(a, \beta) = \alpha$ if and only if i is bijective. \square

As a consequence, the λ -theories induced by relational graph models and by ordinary graph models are different, since no graph model is extensional.

Concerning the models of Example 3.10 we show that \mathcal{E} induces the same λ -theory as Engeler's model [38] and the same inequational theory as the filter model defined by Ronchi Della Rocca in [70] (Theorem 5.6). Moreover such theories are minimal among those representable by relational graph models (Theorem 5.7). The model \mathcal{D}_ω has the same inequational and λ -theories as Scott's \mathcal{D}_∞ [75], namely it is fully abstract for \mathcal{H}^* (Corollary 7.16). The model \mathcal{D}_\star induces the same inequational and λ -theories as Coppo, Dezani-Ciancaglini and Zacchi's filter model [25], namely it is fully abstract for \mathcal{H}^+ (Corollary 6.9).

4. QUANTITATIVE PROPERTIES AND APPROXIMATION THEOREM

Every relational graph model can be presented as a type system. The interpretation of a λ -term M is given by the set of all pairs (Γ, α) such that $\Gamma \vdash M : \alpha$ is derivable in the system. Such a *logical* interpretation turns out to be equivalent to the categorical one (Theorem 4.8). This presentation exposes the *quantitative* nature of the relational semantics and allows to provide a combinatorial proof of the Approximation Theorem (Theorem 4.15).

$$\boxed{
\begin{array}{c}
\frac{}{x : [\alpha] \vdash_{\mathcal{D}} x : \alpha} \text{var} \qquad \frac{\Gamma, x : a \vdash_{\mathcal{D}} M : \alpha}{\Gamma \vdash_{\mathcal{D}} \lambda x.M : a \rightarrow \alpha} \text{lam} \\
\\
\frac{\Gamma \vdash_{\mathcal{D}} M : [\beta_1, \dots, \beta_n] \rightarrow \alpha \quad \Delta_i \vdash_{\mathcal{D}} N : \beta_i \quad 1 \leq i \leq n}{\Gamma + (\sum_{i=1}^n \Delta_i) \vdash_{\mathcal{D}} MN : \alpha} \text{app}
\end{array}
}$$

Figure 4: The typing rules of the type system associated with a relational graph model \mathcal{D} .

4.1. Relational Graph Models as Type Systems. The *types* of the system associated to a relational graph model \mathcal{D} are the elements of the underlying set D themselves.

Definition 4.1. An *environment* for \mathcal{D} is a map $\Gamma : \text{Var} \rightarrow \mathcal{M}_f(D)$ such that $\text{supp}(\Gamma) = \{x \in \text{Var} \mid \Gamma(x) \neq \omega\}$ is finite. The set of all environments for \mathcal{D} is denoted by $\text{Env}_{\mathcal{D}}$.

We write $x_1 : a_1, \dots, x_n : a_n$ for the environment Γ such that $\Gamma(x_i) = a_i$ if $1 \leq i \leq n$ and $\Gamma(y) = \omega$ otherwise. When $\text{supp}(\Gamma) = \emptyset$ the environment Γ is just omitted.

Definition 4.2. Given $\Gamma, \Delta \in \text{Env}_{\mathcal{D}}$ we define the environment $\Gamma + \Delta$ by setting $(\Gamma + \Delta)(x) = \Gamma(x) + \Delta(x)$ for all $x \in \text{Var}$.

A *(type) judgment* is a triple $(\Gamma, M, \alpha) \in \text{Env}_{\mathcal{D}} \times \Lambda_{\perp} \times D$ that will be denoted as $\Gamma \vdash_{\mathcal{D}} M : \alpha$, or simply $\Gamma \vdash M : \alpha$ whenever \mathcal{D} is clear from the context.

Definition 4.3. Let \mathcal{D} be an rgm. The inference rules of the *type system* $\vdash_{\mathcal{D}}$ for Λ_{\perp} associated with \mathcal{D} are given in Figure 4.

We remark that these type systems are *relevant* since the weakening is not available. Indeed, the rule **var** does not allow a generic environment $\Gamma, x : [\alpha]$ and the sum of contexts in **app** takes multiplicities into account. The types are *strict* in the sense that multisets may only appear at the left hand-side of an arrow. In particular, no $\lambda\perp$ -term can have type ω .

The number n appearing in the rule **app** can be 0. So we have the inference rule

$$\frac{\Gamma \vdash_{\mathcal{D}} M : \omega \rightarrow \alpha}{\Gamma \vdash_{\mathcal{D}} MN : \alpha} \tag{4.1}$$

for every $N \in \Lambda_{\perp}$. For example, even if Ω is not typable in the system associated with any relational graph model, the following derivation is always possible for every $\alpha \in D$:

$$\frac{\frac{x : \omega \rightarrow \alpha \vdash x : \omega \rightarrow \alpha}{x : \omega \rightarrow \alpha \vdash x \Omega : \alpha}}{\vdash \lambda x.x \Omega : (\omega \rightarrow \alpha) \rightarrow \alpha}$$

Hereafter, when writing $\Gamma \vdash M : \alpha$, we intend that such a judgment is derivable. We write $\pi \blacktriangleright \Gamma \vdash M : \alpha$ to indicate that π is a derivation tree of the judgment $\Gamma \vdash M : \alpha$.

Definition 4.4. Let π, π' be two derivation trees. We set $\pi \simeq \pi'$ if and only if the trees obtained from π and π' by removing the $\lambda\perp$ -terms from each of their nodes coincide.

Example 4.5. Let π and π' be the following derivation trees:

$$\begin{array}{c}
\frac{x : \alpha \vdash_{\mathcal{D}} x : \alpha}{x : \alpha \vdash_{\mathcal{D}} \lambda y.x : \omega \rightarrow \alpha} \\
\frac{x : \alpha \vdash_{\mathcal{D}} \lambda y.x : \omega \rightarrow \alpha}{x : \alpha \vdash_{\mathcal{D}} (\lambda y.x) z : \alpha}
\end{array}
\qquad
\begin{array}{c}
\frac{x : \alpha \vdash_{\mathcal{D}} x : \alpha}{x : \alpha \vdash_{\mathcal{D}} \lambda y.x : \omega \rightarrow \alpha} \\
\frac{x : \alpha \vdash_{\mathcal{D}} \lambda y.x : \omega \rightarrow \alpha}{x : \alpha \vdash_{\mathcal{D}} (\lambda y.x) \mathbf{K} : \alpha}
\end{array}$$

We have $\pi \simeq \pi'$ because once all $\lambda\perp$ -terms are erased they both become like this:

$$\frac{\frac{x : \alpha \vdash_{\mathcal{D}} : \alpha}{x : \alpha \vdash_{\mathcal{D}} : \omega \rightarrow \alpha}}{x : \alpha \vdash_{\mathcal{D}} : \alpha}$$

From an intuitive perspective, the equivalence $\pi \simeq \pi'$ says that π and π' are roughly the *same* derivation tree (but can be possibly used to type distinct $\lambda\perp$ -terms).

Lemma 4.6. *Let \mathcal{D} be an rgm. If $\Gamma \vdash_{\mathcal{D}} M : \alpha$ then $\text{supp}(\Gamma) \subseteq \text{FV}(M)$.*

Proof. By a straightforward induction on the derivation of the judgment. \square

As shown by the first derivation of Example 4.5, the inclusion in Lemma 4.6 can be strict, indeed we have $x : \alpha \vdash (\lambda y.x)z$ and $\text{supp}(x : \alpha) = \{x\} \subsetneq \text{FV}((\lambda y.x)z)$. In general, one should realize that whenever $\pi \blacktriangleright \Gamma \vdash M : \alpha$ and $\text{supp}(\Gamma) \subsetneq \text{FV}(M)$ then along π some subterm N of M comes in argument position and is not actually typed, as in (4.1).

We could formalize the type systems $\vdash_{\mathcal{D}}$ in a style more similar to traditional intersection type systems, in order to expose clearly the intuition of relational graph models as resource-sensitive versions of filter models [8, Part III], not only of graph models. We followed that approach in [62] and [72], where not only the multisets occurring in the types were actually denoted as non-idempotent intersections, but also an explicit conversion rule:

$$\frac{\Gamma \vdash_{\mathcal{D}} M : \beta \quad \beta \simeq \alpha}{\Gamma \vdash_{\mathcal{D}} M : \alpha} \text{eq}$$

was available in the system. Since such a presentation does not change the expressive power of the systems, but complicates the technical proofs (as it obliges to consider the possible commutations of the rule **eq** along a given derivation π) we decided to avoid it here.

4.2. Logical Interpretation. The type system associated to a relational graph model \mathcal{D} provides an alternative way to define the interpretation of a $\lambda\perp$ -term. This *logical/type-theoretical* approach is rather common and fits in the tradition of filter models [8, Part III].

Definition 4.7. Let \mathcal{D} be an rgm and $M \in \Lambda_{\perp}$. The *logical interpretation* of M in \mathcal{D} is:

$$\llbracket M \rrbracket^{\mathcal{D}} = \{ (\Gamma, \alpha) \in \text{Env}_{\mathcal{D}} \times D \mid \Gamma \vdash_{\mathcal{D}} M : \alpha \}.$$

When \mathcal{D} is clear from the context we write $\llbracket M \rrbracket$, and when M is closed we consider $\llbracket M \rrbracket \subseteq D$. This definition extends to Böhm trees of λ -terms like Definition 3.11.

The interpretation of a $\lambda\perp$ -term cannot be just the set of its types as in the case of filter models. This is related with the fact that **MRel** is not well-pointed (see Section 4.3).

We now show that the logical interpretation $\llbracket - \rrbracket^{\mathcal{D}}$ is equivalent to the categorical one $| - |_{\mathcal{D}}$ in the sense that they induce the same (in)equalities between λ -terms.

Theorem 4.8 (Semantic Equivalence). Let $M \in \Lambda$ and $\text{FV}(M) \subseteq \{x_1, \dots, x_n\}$. Then

- (i) $\llbracket M \rrbracket^{\mathcal{D}} = \left\{ (\Gamma, \alpha) \in \text{Env}_{\mathcal{D}} \times D \mid ((\Gamma(x_1), \dots, \Gamma(x_n)), \alpha) \in |M|_{\vec{x}}^{\mathcal{D}} \right\},$
- (ii) $|M|_{\vec{x}}^{\mathcal{D}} = \left\{ ((\Gamma(x_1), \dots, \Gamma(x_n)), \alpha) \in \mathcal{M}_{\text{f}}(D)^n \times D \mid (\Gamma, \alpha) \in \llbracket M \rrbracket^{\mathcal{D}} \right\}.$

Proof. It is enough to prove that $\Gamma \vdash M : \alpha$ if and only if $((\Gamma(x_1), \dots, \Gamma(x_n), \alpha)) \in |M|_{\vec{x}}$, namely Point (i). Point (ii) follows since every $((a_1, \dots, a_n), \alpha) \in \mathcal{M}_f(D)^n \times D$ has the form $((\Gamma(x_1), \dots, \Gamma(x_n)), \alpha)$ for some $\Gamma \in \text{Env}_{\mathcal{D}}$. We proceed by induction on M .

Case $M = x_i$. By Definition 4.3 we have $\Gamma \vdash x_i : \alpha$ if and only if $\Gamma = x_i : [\alpha]$. Thus, we have $((\Gamma(x_1), \dots, \Gamma(x_n)), \alpha) = ((\omega, \dots, \omega, [\alpha], \omega, \dots, \omega), \alpha) \in |x_i|_{\vec{x}}$ by Definition 3.11(i).

Case $M = \lambda y.P$. By Definition 4.3 we have $\Gamma \vdash \lambda y.P : \alpha$ exactly when $\Gamma, y : a \vdash P : \alpha$. By induction hypothesis this is equivalent to $((\Gamma(x_1), \dots, \Gamma(x_n), a), \alpha) \in |P|_{\vec{x}, y}$ which holds if and only if $((\Gamma(x_1), \dots, \Gamma(x_n)), a \rightarrow \alpha) \in |\lambda y.P|_{\vec{x}}$, by Definition 3.11(ii).

Case $M = PQ$. By Definition 4.3 we have $\Gamma \vdash PQ : \alpha$ if and only if $\Gamma_0 \vdash P : [\beta_1, \dots, \beta_k] \rightarrow \alpha$ and $\Gamma_i \vdash Q : \beta_i$ for all $1 \leq i \leq k$ where $\Gamma = \sum_{i=0}^n \Gamma_i$ and $\beta_1, \dots, \beta_k \in D$. By induction hypothesis this is equivalent to $((\Gamma_0(x_1), \dots, \Gamma_0(x_n)), [\beta_1, \dots, \beta_k] \rightarrow \alpha) \in |P|_{\vec{x}}$ and $((\Gamma_i(x_1), \dots, \Gamma_i(x_n)), \beta_i) \in |Q|_{\vec{x}}$ for all $1 \leq i \leq k$. We conclude because this is equivalent to $((\Gamma(x_1), \dots, \Gamma(x_n)), \alpha) \in |PQ|_{\vec{x}}$ by Definition 3.11(iii). \square

Corollary 4.9. *Let \mathcal{D} be an rgm. Let $M, N \in \Lambda$ such that $\text{FV}(MN) \subseteq \{x_1, \dots, x_n\}$. Then*

$$\mathcal{D} \models M \sqsubseteq N \iff |M|_{\vec{x}}^{\mathcal{D}} \subseteq |N|_{\vec{x}}^{\mathcal{D}} \iff \llbracket M \rrbracket^{\mathcal{D}} \subseteq \llbracket N \rrbracket^{\mathcal{D}}.$$

4.3. On the choice of the interpretation. The categorical interpretation of a λ -term M in a reflexive object \mathcal{D} gives a morphism $|M|_{\vec{x}} : D^{\vec{x}} \rightarrow D$ such that $\text{Th}(\mathcal{D})$ is a λ -theory. If the category is well-pointed, like Scott's continuous semantics, then it is equivalent to interpret M as a *point* of D through a *valuation* $\rho : \text{Var} \rightarrow D$, namely $|M|_{\rho} : \top \rightarrow D$ [6, §5.5]. For this reason, in the context of graph and filter models, it became standard to consider the interpretation of M as an element of the domain and, when presented like a type system, as the set of its types [9, 25, 70, 71]. As shown by Koymans in [51], when the category is not well-pointed, points are no more suitable for interpreting λ -terms since the induced equality is not a λ -theory because of the failure of the ξ -rule [77]. In the algebraic terminology, the set of points gives a λ -algebra which is not a λ -model [6, §5.2]. In [19], Bucciarelli *et al.* show that a λ -model can however be constructed from a reflexive object \mathcal{D} of a non-well pointed category, by considering the set of $\mathbf{C}_f(D^{\text{Var}}, D)$ of “finitary” morphisms from D^{Var} to D and valuations $\rho : \text{Var} \rightarrow \mathbf{C}_f(D^{\text{Var}}, D)$. For instance, this is the approach followed in [66]. However, in [59], the author remarks that the use of valuations in this context becomes redundant since $|M|_{\rho} = |N|_{\rho}$ exactly when they are equal under the valuation $x \mapsto \pi_x^{\text{Var}}$ sending x to the corresponding projection. By applying this fact to the logical interpretation given in [66], we recover Definition 4.7 and this justifies Theorem 4.8 from a broader perspective. See [19, 77, 59] for more detailed discussions on well-pointedness.

4.4. Quantitative Properties. We show some quantitative properties satisfied by the type systems issued from a relational graph model. We refer to the technical Appendix A for the proofs of Lemma 4.10 and Lemma 4.13. Until the end of the section, the symbol \vdash refers to any fixed relational graph model.

Let $\# \text{app}(\pi)$ be the number of instances of the rule **app** that occur in the derivation π .

Lemma 4.10 (Weighted Substitution Lemma). *Let $M, N \in \Lambda_{\perp}$. Consider some derivations $\pi_0 \blacktriangleright \Gamma_0, x : [\beta_1, \dots, \beta_n] \vdash M : \alpha$ for $n \in \mathbb{N}$ and $\pi_i \blacktriangleright \Gamma_i \vdash N : \beta_i$ for all $1 \leq i \leq n$. Then there exists $\pi \blacktriangleright \sum_{i=0}^n \Gamma_i \vdash M\{N/x\} : \alpha$ such that $\# \text{app}(\pi) = \sum_{i=0}^n \# \text{app}(\pi_i)$.*

From this, it follows that the number of rules **app** in the derivation of a β -redex, decrements in a derivation of its contractum.

Corollary 4.11. *Let $M, N \in \Lambda_\perp$. If $\pi \blacktriangleright \Gamma \vdash (\lambda x.M)N : \alpha$ there exists a derivation π' such that $\pi' \blacktriangleright \Gamma \vdash M\{N/x\} : \alpha$ with $\#app(\pi') = \#app(\pi) - 1$.*

Proof. The derivation π has the form

$$\frac{\frac{\pi_0 \blacktriangleright \Gamma_0, x : [\beta_1, \dots, \beta_n] \vdash M : \alpha}{\Gamma_0 \vdash \lambda x.M : [\beta_1, \dots, \beta_n] \rightarrow \alpha} \text{lam} \quad \pi_i \blacktriangleright \Gamma_i \vdash N : \beta_i \text{ for all } 1 \leq i \leq n}{\sum_{i=0}^n \Gamma_i \vdash (\lambda x.M)N : \alpha} \text{app}$$

where $n \in \mathbb{N}$ and $\Gamma = \sum_{i=0}^n \Gamma_i$. By Lemma 4.10 there is $\pi' \blacktriangleright \sum_{i=0}^n \Gamma_i \vdash M\{N/x\} : \alpha$ such that $\#app(\pi') = \sum_{i=0}^n \#app(\pi_i) = \#app(\pi) - 1$. \square

From Corollary 4.11 it follows that the number of **app** decreases exactly by 1 at each step of head reduction. So $\#app(-)$ provides an upper bound for the number of steps necessary to get the principal hnf of a solvable term, as observed by de Carvalho in [29].

Lemma 4.12. If $\pi \blacktriangleright \Gamma \vdash M : \alpha$ then the head reduction of M has length at most $\#app(\pi)$.

Unfortunately, the measure $\#app(-)$ is not enough for proving the approximation theorem. The reason is that, in order to compute the Böhm tree of a λ -term M , one needs to reduce also redexes that are not in head-position. E.g., consider the following derivation π :

$$\frac{x : \omega \rightarrow \alpha \vdash x : \omega \rightarrow \alpha}{x : \omega \rightarrow \alpha \vdash x(\mathbf{I}y) : \alpha} \text{app}$$

When reducing $x(\mathbf{I}y) \rightarrow_\beta xy$, the only possible derivation π' of $x : \omega \rightarrow \alpha \vdash xy : \alpha$ is:

$$\frac{x : \omega \rightarrow \alpha \vdash x : \omega \rightarrow \alpha}{x : \omega \rightarrow \alpha \vdash xy : \alpha} \text{app}$$

The number of **app** has not decreased in this case, so we cannot use $\#app(-)$ as a decreasing measure in the proof of the left-to-right implication of Theorem 4.15. We can however find an approximant $t \in \text{BT}^*(x(\mathbf{I}y))$ with that typing by realizing that in π the subterm $\mathbf{I}y$ is basically used as the approximant \perp . This is the key idea behind the next lemma.

Given $M \in \Lambda_\perp$ and a redex occurrence $R = (\lambda x.P)Q$ in M , say $M = C[R]$ for some single hole $\lambda\perp$ -context $C[-]$, we denote by $M\{\perp/R\}$ the $\lambda\perp$ -term $C[\perp]$. Moreover, we write $M \xrightarrow{R}_\beta M'$ to indicate that the contracted β -redex is R , namely that $M' = C[P\{Q/x\}]$.

Lemma 4.13 (Weighted Subject Reduction). Let $M, M' \in \Lambda_\perp$ be such that $M \xrightarrow{R}_\beta M'$. If $\pi \blacktriangleright \Gamma \vdash M : \alpha$, then there is $\pi' \blacktriangleright \Gamma \vdash M' : \alpha$ such that one of the following cases holds:

- (i) $\#app(\pi') < \#app(\pi)$,
- (ii) $\pi' \simeq \pi$ and there exists $\pi'' \blacktriangleright \Gamma \vdash M\{\perp/R\} : \alpha$ such that $\pi'' \simeq \pi$.

As a note aside, Lemma 4.13 gives in particular the subject reduction property. The subject expansion can be proved equally easily, as done in [72, §2.4]. These two properties provide yet another soundness proof for relational graph models.

4.5. The Approximation Theorem. We show that all relational graph models satisfies the Approximation Theorem stating that the interpretation of a λ -term is given by the union of the interpretations of its finite approximants (Theorem 4.15). As mentioned in the introduction, we provide a new combinatorial proof that does not exploits reducibility candidates nor Ehrhard's notion of Taylor expansion. Actually, it is an easy consequence of our Weighted Subject Reduction (Lemma 4.13).

From the Approximation Theorem, we get that the λ -theory induced by any relational graph model \mathcal{D} includes \mathcal{B} (Corollary 4.16) and, if \mathcal{D} is extensional, also \mathcal{H}^+ (Corollary 4.17).

Lemma 4.14. Let $M \in \Lambda_\perp$. If M is β -normal and $\Gamma \vdash M : \alpha$ then $\Gamma \vdash \text{da}(M) : \alpha$.

Proof. By a straightforward induction on M . \square

Notice that the hypothesis that M is in β -nf is necessary to prove Lemma 4.14. Indeed, for $M = \mathbf{I}x$ we have $x : [\alpha] \vdash M : \alpha$, whereas $\text{da}(M) = \perp$ cannot be typed.

Given $M \in \Lambda_\perp$ we denote by $\#\text{red}_\beta(M)$ the number of β -redexes occurring in M .

Theorem 4.15 (Approximation Theorem). Let $M \in \Lambda_\perp$. Then $(\Gamma, \alpha) \in \llbracket M \rrbracket$ if and only if there exists $t \in \text{BT}^*(M)$ such that $(\Gamma, \alpha) \in \llbracket t \rrbracket$. Therefore $\llbracket M \rrbracket = \bigcup_{t \in \text{BT}^*(M)} \llbracket t \rrbracket$.

Proof. (\Rightarrow) Let $\pi \blacktriangleright \Gamma \vdash M : \alpha$. We proceed by induction on the pair $(\#\text{app}(\pi), \#\text{red}_\beta(M))$ lexicographically ordered.

Case $\#\text{red}_\beta(M) = 0$. By Lemma 4.14 $\Gamma \vdash \text{da}(M) : \alpha$ and clearly $\text{da}(M) \in \text{BT}^*(M)$.

Case $\#\text{red}_\beta(M) > 0$. Let R be any β -redex of M and $M \xrightarrow{R}_\beta M'$. By Lemma 4.13 there is $\pi' \blacktriangleright \Gamma \vdash M' : \alpha$ such that either (i) $\#\text{app}(\pi') < \#\text{app}(\pi)$, or (ii) there exists $\pi'' \blacktriangleright \Gamma \vdash M\{\perp/R\} : \alpha$ such that $\pi'' \simeq \pi$.

In Case (i) we apply the induction hypothesis to π' and get $t \in \text{BT}^*(M') = \text{BT}^*(M)$ such that $\Gamma \vdash t : \alpha$.

In Case (ii) we can apply the induction hypothesis to π'' , as $\pi'' \simeq \pi$ implies $\#\text{app}(\pi'') = \#\text{app}(\pi)$, and moreover $\#\text{red}_\beta(\pi'') < \#\text{red}_\beta(\pi)$. We get $t \in \text{BT}^*(M\{\perp/R\})$ such that $\Gamma \vdash t : \alpha$. Since moreover $\text{BT}^*(M\{\perp/R\}) \subseteq \text{BT}^*(M)$ by Lemma 1.16, we are done.

(\Leftarrow) We proceed by induction on t . The case $t = \perp$ is vacuous, as \perp is not typable. So let $t = \lambda x_1 \dots x_n. x t_1 \dots t_m$ where $n, m \in \mathbb{N}$. We suppose that the variable x is bound, the other case being analogous. The given derivation tree of $\Gamma \vdash t : \alpha$ must have the form

$$\frac{\frac{\Delta \vdash x : b_1 \rightarrow \dots \rightarrow b_m \rightarrow \beta \quad \Gamma_{ij}, x_1 : a_1^{ij}, \dots, x_n : a_n^{ij} \vdash t_i : \beta_{ij} \quad \text{for all } i, j}{\sum_{i=1}^m \sum_{j=1}^{k_i} \Gamma_{ij}, x_1 : \sum_{i=1}^m \sum_{j=1}^{k_i} a_1^{ij}, \dots, x_n : \sum_{i=1}^m \sum_{j=1}^{k_i} a_n^{ij} \vdash x t_1 \dots t_m : \beta}}{\Gamma \vdash \lambda x_1 \dots x_n. x t_1 \dots t_m : a_1 \rightarrow \dots \rightarrow a_n \rightarrow \beta}$$

where for all $i \leq m$ we have $b_i = [\beta_{i1}, \dots, \beta_{ik_i}]$ for some $k_i \in \mathbb{N}$; $\Delta = x : b_1 \rightarrow \dots \rightarrow b_m \rightarrow \beta$; $\Gamma = \Delta + \sum_{i=1}^m \sum_{j=1}^{k_i} \Gamma_{ij}$; $a_\ell = \sum_{i=1}^m \sum_{j=1}^{k_i} a_\ell^{ij}$ for all $\ell \leq n$; finally, $\alpha = a_1 \rightarrow \dots \rightarrow a_n \rightarrow \beta$. As $t \in \text{BT}^*(M)$ we have that $t = \text{da}(N)$ for some $N =_\beta M$. By Definition 1.15, we have $N = \lambda x_1 \dots x_n. x N_1 \dots N_m$ with $t_i = \text{da}(N_i)$ for all $i \leq m$. By induction hypothesis we get $\Gamma_{ij}, x_1 : a_1^{ij}, \dots, x_n : a_n^{ij} \vdash N_i : \beta_{ij}$ for all i, j . By replacing each t_i by N_i in the proof tree above, we get a derivation of $\Gamma \vdash N : \alpha$. Since $N =_\beta M$, by soundness we get $\Gamma \vdash M : \alpha$. \square

Corollary 4.16. For all rgm's \mathcal{D} we have that $\mathcal{B} \subseteq \text{Th}(\mathcal{D})$. In particular $\text{Th}(\mathcal{D})$ is sensible and $\llbracket M \rrbracket^\mathcal{D} = \emptyset$ for all unsolvable λ -terms M .

Proof. From Theorem 4.15 we get $\llbracket M \rrbracket = \llbracket \text{BT}(M) \rrbracket = \bigcup_{t \in \text{BT}^*(M)} \llbracket t \rrbracket$. Therefore, whenever $\text{BT}(M) = \text{BT}(N)$ we have $\llbracket M \rrbracket = \llbracket \text{BT}(M) \rrbracket = \llbracket \text{BT}(N) \rrbracket = \llbracket N \rrbracket$. Thus $\mathcal{B} \subseteq \text{Th}(\mathcal{D})$. \square

In the next corollary we are going to use the Lévy's characterization of Morris's inequational theory $\sqsubseteq_{\mathcal{H}^+}$ in terms of extensional approximants (Theorem 2.17).

Corollary 4.17. *For an rgm \mathcal{D} , the following are equivalent:*

- (i) \mathcal{D} is extensional,
- (ii) $\sqsubseteq_{\mathcal{H}^+} \subseteq \text{Th}_{\sqsubseteq}(\mathcal{D})$,
- (iii) $\mathcal{H}^+ \subseteq \text{Th}(\mathcal{D})$.

Proof. (i \Rightarrow ii) From Theorem 4.15 we obtain $\llbracket M \rrbracket = \bigcup_{t \in \text{BT}^*(M)} \llbracket t \rrbracket$. From the extensionality of \mathcal{D} , we get $\llbracket M \rrbracket = \bigcup_{M' \twoheadrightarrow_{\eta} M, t \in \text{BT}^*(M')} \llbracket t \rrbracket = \bigcup_{M' \twoheadrightarrow_{\eta} M, t \in \text{BT}^*(M')} \llbracket \text{nf}_{\eta}(t) \rrbracket = \llbracket \text{BT}^e(M) \rrbracket$. So, we have that $\text{BT}^e(M) \subseteq \text{BT}^e(N)$ entails $\llbracket M \rrbracket = \llbracket \text{BT}^e(M) \rrbracket \subseteq \llbracket \text{BT}^e(N) \rrbracket = \llbracket N \rrbracket$.

(ii \Rightarrow iii) Trivial.

(iii \Rightarrow i) By Lemma 3.17. □

5. THE MINIMAL RELATIONAL GRAPH THEORY

In this section we show that a minimal inequational graph theory exists, and that it is exactly the inequational theory induced by the model \mathcal{E} defined in Example 3.10.

5.1. The Minimal Inequational Graph Theory. We start by defining an inequational theory \sqsubseteq_r and prove that it is included in $\text{Th}_{\sqsubseteq}(\mathcal{D})$ for every relational graph model \mathcal{D} .

Definition 5.1. Given $M, N \in \Lambda$, we let $M \sqsubseteq_r N$ whenever there exists a Böhm-like tree U such that $\text{BT}(M) \leq_{\perp} U \geq_{\infty}^{\eta} \text{BT}(N)$.

The fact that this definition involves η -expansions and that $\sqsubseteq_r \subseteq \text{Th}_{\sqsubseteq}(\mathcal{D})$ holds also for non-extensional relational graph models should not be surprising. Indeed, when considering the original graph model \mathcal{P}_{ω} defined by Plotkin [68] and Scott [76] the situation is actually analogous (but symmetrical³), and no graph model is extensional.

Example 5.2.

- (1) $\mathbf{J} \sqsubseteq_r \mathbf{I}$ while $\mathbf{I} \not\sqsubseteq_r \mathbf{J}$,
- (2) Let $(M)_{n \in \mathbb{N}}$ be the effective sequence defined by $M_n = \mathbf{J}$ if n is even and $M_n = \Omega$ otherwise. Then we have $[M_n]_{n \in \mathbb{N}} \sqsubseteq_r [\mathbf{I}]_{n \in \mathbb{N}}$.

It follows from [70] that $M \sqsubseteq_r N \sqsubseteq_r M$ if and only if $\mathcal{B} \vdash M = N$. The inequational theory \sqsubseteq_r admits the following characterization in terms of Böhm tree approximants.

Lemma 5.3. Let $M, N \in \Lambda$. We have $M \sqsubseteq_r N$ if and only if for all $t \in \text{BT}^*(M)$ there exists $s \in \text{BT}^*(N)$ such that $t \leq_{\perp} u \twoheadrightarrow_{\eta} s$ for some $u \in \text{NF}_{\beta\perp}$.

Proof. (\Rightarrow) By structural induction on t . If $t = \perp$, then we can take $s = u = \text{da}(M)$.

Otherwise $t \neq \perp$ entails that M has an hnf $M =_{\beta} \lambda \vec{x} \vec{z}. x_i M_1 \cdots M_k P_1 \cdots P_m$. By Definition 5.1, there is a Böhm-like tree $U = \lambda \vec{x} z_1 \dots z_m. x_i U_1 \cdots U_k V_1 \cdots V_m$ such that $\text{BT}(M_j) \leq_{\perp} U_j$ and $\text{BT}(P_{\ell}) \leq_{\perp} V_{\ell} \geq_{\infty}^{\eta} z_{\ell}$, and $N =_{\beta} \lambda \vec{x}. x_i N_1 \cdots N_k$ with $U_j \geq_{\infty}^{\eta} \text{BT}(N_j)$. Thus, we have $t = \lambda \vec{x} \vec{z}. x_i t_1 \cdots t_k t'_1 \cdots t'_m$ for $t_j \in \text{BT}^*(M_j)$ and $t'_{\ell} \in \text{BT}^*(P_{\ell})$. Since for all $j \leq k$ we have $M_j \sqsubseteq_r N_j$ and for all $\ell \leq m$ we have $P_{\ell} \sqsubseteq_r z_{\ell}$ we can apply the induction hypothesis and get $t_j \leq_{\perp} u_j \twoheadrightarrow_{\eta} s_j$ for some $s_j \in \text{BT}^*(N_j)$ and $t'_{\ell} \leq_{\perp} u'_{\ell} \twoheadrightarrow_{\eta} z_{\ell}$. As a consequence $t \leq_{\perp} \lambda \vec{x} z_1 \dots z_m. x_i u_1 \cdots u_k u'_1 \cdots u'_m \twoheadrightarrow_{\eta} \lambda \vec{x}. x_i s_1 \cdots s_k \in \text{BT}^*(N)$.

³ I.e. $\mathcal{P}_{\omega} \models M \sqsubseteq N$ exactly when there is a Böhm-like tree U such that $\text{BT}(M) \leq_{\infty}^{\eta} U \leq_{\perp} \text{BT}(N)$ [46].

(\Leftarrow) We proceed coinductively on the Böhm trees. If M is unsolvable, then we are done.

Otherwise there is $t \in \text{BT}^*(M)$ of the form $t = \lambda \vec{x} z_1 \dots z_m. x_i t_1 \dots t_k t'_1 \dots t'_m$ and $s = \lambda \vec{x}. x_i s_1 \dots s_k \in \text{BT}^*(N)$ such that $t \leq_\perp \lambda \vec{x} \vec{z}. x_i u_1 \dots u_k u'_1 \dots u'_m \twoheadrightarrow_\eta s$. This entails that $M =_\beta \lambda \vec{x} \vec{z}. x_i M_1 \dots M_k P_1 \dots P_m$ and $N =_\beta \lambda \vec{x}. x_i N_1 \dots N_k$ with $t_j \in \text{BT}^*(M_j)$, $s_j \in \text{BT}^*(N_j)$ for all $j \leq k$, $z_\ell \notin \text{FV}(\text{BT}(x_i \vec{M} \vec{N}))$, and $t'_\ell \in \text{BT}^*(P_\ell)$ for all $\ell \leq m$. By coinductive hypothesis there are Böhm-like trees U_j such that $\text{BT}(M_j) \leq_\perp U_j \geq_\infty^\eta \text{BT}(N_j)$. Since for all $t'_\ell \in \text{BT}^*(P_\ell)$ there is an η -expansion u'_ℓ of z_ℓ such that $t'_\ell \leq_\perp u'_\ell$, then there exists a Böhm-like tree V_ℓ such that $\text{BT}(P_\ell) \leq_\perp V_\ell \geq_\infty^\eta z_\ell$. As a consequence $\text{BT}(M) \leq_\perp \lambda \vec{x} \vec{z}. x_i U_1 \dots U_k V_1 \dots V_m \geq_\infty^\eta \text{BT}(N)$, which implies $M \sqsubseteq_r N$. \square

Proposition 5.4. Let $M, N \in \Lambda$. If $M \sqsubseteq_r N$ then $\mathcal{D} \models M \sqsubseteq N$ for every rgm \mathcal{D} .

Proof. By Lemma 5.3 for all $t \in \text{BT}^*(M)$ there are $s \in \text{BT}^*(N)$ and $u \in \text{NF}_{\beta\perp}$ such that $t \leq_\perp u \twoheadrightarrow_\eta s$. Since $t \leq_\perp u$ we get $t \in \text{BT}^*(u)$ and, by Theorem 4.15, we obtain $\llbracket t \rrbracket \subseteq \llbracket u \rrbracket$. From Lemma 3.17(i) and Corollary 4.9 we have that $\llbracket u \rrbracket \subseteq \llbracket s \rrbracket$ holds. It follows that $\llbracket \text{BT}(M) \rrbracket \subseteq \llbracket \text{BT}(N) \rrbracket$, so we conclude by applying Theorem 4.15. \square

We now show that \sqsubseteq_r is representable by some relational graph model.

5.2. The Model \mathcal{E} Induces Minimal Theories. Let $\mathcal{E} = (E, \iota)$ be the relational graph model defined in Example 3.10. This model has infinitely many atoms, that we denote by $(\xi_n)_{n \in \mathbb{N}}$, and as injection $\iota : \mathcal{M}_f(E) \times E \rightarrow E$ simply the inclusion, therefore no atom ξ_n can be equal to an arrow $a \rightarrow_\iota \alpha$. In other words, the elements $\alpha \in E$ are generated by:

$$\alpha ::= \xi_n \mid a \rightarrow \alpha \quad a ::= [\alpha_1, \dots, \alpha_k] \quad (\text{for } n, k \geq 0).$$

The type inference rules given in Figure 4 remain unchanged. We are going to show that the interpretations of M, N are different whenever $M \not\sqsubseteq_r N$.

Notice that every element $\alpha \in E$ can be written uniquely as $\alpha = a_1 \rightarrow \dots \rightarrow a_n \rightarrow \xi_i$. In this case, the atom ξ_i is called the *range of α* and denoted by $\text{rg}(\alpha)$. We use the compact notation $\omega^k \rightarrow \alpha$ to denote the element $\omega \rightarrow \dots \rightarrow \omega \rightarrow \alpha$ (with k occurrences of ω).

Recall that the size $\#t$ of $t \in \text{NF}_{\beta\perp}$ has been introduced in Definition 1.14.

Lemma 5.5. Let $M, N \in \Lambda$. If $M \sqsubseteq_{\mathcal{H}^*} N$ but $M \not\sqsubseteq_r N$, then there are Γ, α such that:

- (i) $\Gamma \vdash_{\mathcal{E}} t : \alpha$ for some $t \in \text{BT}^*(M)$,
- (ii) for all $u \in \text{BT}^*(N)$ we have $\Gamma \not\vdash_{\mathcal{E}} u : \alpha$,
- (iii) $\text{rg}(\alpha) = \xi_{\#t}$,
- (iv) for all $\beta \in \Gamma$, $\text{rg}(\beta) = \xi_j$ for some $j \leq \#t$.

Proof. Since $M \not\sqsubseteq_r N$, we have that M must be solvable. As moreover $M \sqsubseteq_{\mathcal{H}^*} N$, by Remark 2.7 we get that M, N have similar hnf's. Therefore, only two cases are possible.

1) $M =_\beta \lambda x_1 \dots x_n. x_i M_1 \dots M_k$ and $N =_\beta \lambda \vec{x} z_1 \dots z_m. x_i N_1 \dots N_k P_1 \dots P_m$ for $m > 0$. We suppose that x_i is free, the other case being analogue. This case follows easily by taking $t = \lambda \vec{x}. x_i \perp \dots \perp \in \text{BT}^*(M)$ whose size is $n + 1$, $\Gamma = x_i : [\omega^k \rightarrow \xi_{n+1}]$ and $\alpha = \omega^n \rightarrow \xi_{n+1}$. The fact that $\Gamma \not\vdash u : \alpha$ for all $u = \lambda \vec{x} \vec{z}. x_i u_1 \dots u_{k+m} \in \text{BT}^*(N)$ follows from $m > 0$ and the fact that ξ_{n+1} is an atom, hence not equal to any arrow type by definition of \mathcal{E} .

2) $M =_\beta \lambda x_1 \dots x_n z_1 \dots z_m. x_i M_1 \dots M_k P_1 \dots P_m$ and $N =_\beta \lambda \vec{x}. x_i N_1 \dots N_k$ where, for every $\ell \leq m$ there is a Böhm-like tree V such that $\text{BT}(P_\ell) \leq_\perp V \geq_\infty^\eta z_\ell$, for every $j \leq k$ we have $M_j \sqsubseteq_{\mathcal{H}^*} N_j$ but $M_q \not\sqsubseteq_r N_q$ for some q . We suppose that x_i is free, the other case being analogue. By induction hypothesis, there is $t_q \in \text{BT}^*(M_q)$ such that $\Gamma \vdash t_q : \alpha$ with

$\text{rg}(\alpha) = \xi_{\#t_q}$, for all $\beta \in \Gamma$ we have $\text{rg}(\beta) = \xi_j$ for some $j \leq \#t_q$ and for all $u_q \in \text{BT}(N_q)$ we have $\Gamma \not\vdash u_q : \alpha$. On the one side, we construct the derivation:

$$\frac{\frac{\Gamma_0 \vdash x_i : \omega^{q-1} \rightarrow [\alpha] \rightarrow \omega^{k+m-q} \rightarrow \xi_{\#t} \quad \Gamma \vdash t_q : \alpha}{\Gamma_0 + \Gamma \vdash x_i t_1 \cdots t_k s_1 \cdots s_m : \xi_{\#t}}}{\Gamma_0 + \Gamma_1 \vdash t = \lambda \vec{x} \vec{z}. x_i t_1 \cdots t_k s_1 \cdots s_m : a_1 \rightarrow \cdots \rightarrow a_n \rightarrow \omega^m \rightarrow \xi_{\#t}}$$

where $\Gamma_0 = x_i : [\omega^{q-1} \rightarrow [\alpha] \rightarrow \omega^{m+k-q} \rightarrow \xi_{\#t}]$, $\Gamma = \Gamma_1 + (x_1 : a_1, \dots, x_n : a_n)$, for all $j \leq k$ we have $t_j \in \text{BT}(M_j)$, and for all $\ell \leq m$ we have $s_\ell \in \text{BT}(P_\ell)$. On the other side, each $u \in \text{BT}(N) - \{\perp\}$ must have the shape $u = \lambda \vec{x}. x_i u_1 \cdots u_k$ and each derivation of $\Gamma_0 + \Gamma_1 \vdash u : \xi_{\#t}$ requires to derive $\Gamma \vdash u_q : \alpha$. Indeed, since all $\beta \in \Gamma$ satisfy $\text{rg}(\beta) \leq \#t_q < \#t$, they cannot be used to produce a $\xi_{\#t}$ so the decomposition of $\Gamma_0 + \Gamma$ is in fact unique:

$$\frac{\frac{\Gamma_0 \vdash x_i : \omega^{q-1} \rightarrow [\alpha] \rightarrow \omega^{m+k-q} \rightarrow \xi_{\#t} \quad \Gamma \vdash u_q : \alpha}{\Gamma_0 + \Gamma \vdash x_i u_1 \cdots u_k : \omega^m \rightarrow \xi_{\#t}}}{\Gamma_0 + \Gamma_1 \vdash u = \lambda \vec{x}. x_i u_1 \cdots u_k : a_1 \rightarrow \cdots \rightarrow a_n \rightarrow \omega^m \rightarrow \xi_{\#t}}$$

By induction hypothesis $\Gamma \vdash u_q : \alpha$ is impossible, which entails $\Gamma_0 + \Gamma_1 \not\vdash u : a_1 \rightarrow \cdots \rightarrow a_n \rightarrow \omega^m \rightarrow \xi_{\#t}$. \square

Theorem 5.6. For $M, N \in \Lambda$ we have

$$M \sqsubseteq_r N \iff \mathcal{E} \models M \sqsubseteq N$$

Therefore $\text{Th}_{\sqsubseteq}(\mathcal{E}) = \sqsubseteq_r$ and $\text{Th}(\mathcal{E}) = \mathcal{B}$.

Proof. (\Rightarrow) It follows immediately by Proposition 5.4.

(\Leftarrow) Suppose, by the way of contradiction, that $M \not\sqsubseteq_r N$ but $\mathcal{E} \models M \sqsubseteq N$. Since $\text{Th}_{\sqsubseteq}(\mathcal{E})$ is sensible, Lemma 2.3 entails $M \sqsubseteq_{\mathcal{H}^*} N$. By Lemma 5.5, there exists $t \in \text{BT}^*(M)$ and Γ, α such that $\Gamma \vdash t : \alpha$ while $\Gamma \not\vdash u : \alpha$ for all $u \in \text{BT}^*(N)$. By the Approximation Theorem, we have $(\Gamma, \alpha) \in \llbracket M \rrbracket - \llbracket N \rrbracket$, which is impossible. \square

The above proof-technique could be suitably generalized to prove that all non-extensional relational graph models induce the same inequational theory, namely \sqsubseteq_r .

Theorem 5.7. The relation \sqsubseteq_r is the minimal inequational graph theory. Similarly, \mathcal{B} is the minimal relational graph theory.

5.3. A Semantic Characterization of Normalizability. We now show that in the model \mathcal{E} β -normalizable λ -terms have a simple semantic characterization. Indeed, since there are no equations between atoms and arrow types, it makes sense to define whether ω occurs in a type α with a certain polarity.

Definition 5.8. Given a *polarity* $p \in \{+, -\}$, we define inductively for all elements α of \mathcal{E} the relations $\omega \in^p \alpha$ and $\alpha \in^{\neg p} \sigma$, where $\neg p$ is the opposite polarity, as follows:

- (i) $\omega \in^- a \rightarrow \beta$ if $a = \omega$;
- (ii) if $\omega \in^p \beta$ then $\omega \in^p a \rightarrow \beta$;
- (iii) if $\omega \in^{\neg p} \beta$ then $\omega \in^p ([\beta] + a) \rightarrow \gamma$.

When $\omega \in^+ \alpha$ (resp. $\omega \in^- \alpha$) we say that ω *occurs positively* (resp. *negatively*) in α . We write $\omega \notin^p \alpha$ whenever α does not occur in α with polarity p .

These notions extend to multisets in the obvious way, that is, $\omega \in^p [\alpha_1, \dots, \alpha_n]$ whenever $\omega \in^p \alpha_i$ for some index i . Similarly, $\omega \in^p \Gamma$ whenever there is $x \in \text{Var}$ such that $\omega \in^p \Gamma(x)$.

Theorem 5.9. Let $M \in \Lambda$. The following are equivalent:

- (1) M has a β -normal form,
- (2) $\Gamma \vdash_{\mathcal{E}} M : \alpha$ for some environment Γ and type α such that $\omega \notin^+ \alpha$ and $\omega \notin^- \Gamma$.

Proof. (1 \Rightarrow 2) Straightforward induction on the derivation of $\Gamma \vdash \text{nf}_{\beta}(M) : \alpha$.

(2 \Rightarrow 1) We proceed by structural induction on the pair (Γ, α) . By Lemma 4.12, M has a head normal form $\lambda x_1 \dots x_n. x_i M_1 \dots M_k$ having type α in the context Γ , which entails $\alpha = a_1 \rightarrow \dots \rightarrow a_n \rightarrow \alpha'$. So, there exists a derivation of the form:

$$\frac{\frac{\Gamma_0 \vdash x_i : b_1 \rightarrow \dots \rightarrow b_k \rightarrow \alpha' \quad \text{var} \quad \Gamma_{j\ell} \vdash M_j : \beta_{j\ell} \quad 1 \leq j \leq k \quad 1 \leq \ell \leq k_j}{\Gamma, x_1 : a_1, \dots, x_n : a_n \vdash x_i M_1 \dots M_k : \alpha'} \text{ app}}{\Gamma \vdash \lambda x_1 \dots x_n. x_i M_1 \dots M_k : \alpha = a_1 \rightarrow \dots \rightarrow a_n \rightarrow \alpha'} \text{ lam}$$

where $\Gamma_0 = [x_i : b_1 \rightarrow \dots \rightarrow b_k \rightarrow \alpha']$, for all $j \leq k$ we have $b_j = [\beta_{j1}, \dots, \beta_{jk_j}]$ and $\Gamma, x_1 : a_1, \dots, x_n : a_n = \Gamma_0 + (\sum_{j=1}^k \sum_{\ell=1}^{k_j} \Gamma_{j\ell})$. Since $\omega \notin^+ \alpha$ and $\omega \notin^- \Gamma$ we get for each $j \leq k$ that b_j is non-empty, and moreover that $\omega \notin^+ \beta_{j\ell}$ and $\omega \notin^- \Gamma_{j\ell}$ for all $\ell \leq k_j$. From the induction hypothesis, we get that all the M_i 's have a β -normal form. \square

As proved in [62], Theorem 5.9 holds for every relational graph model \mathcal{D} *preserving ω -polarities* (in a technical sense). An analogue of this theorem also holds for the usual intersection type systems [7]. However, for an extensional relational graph model \mathcal{D} this lemma is enough to conclude $\text{Th}_{\sqsubseteq}(\mathcal{D}) = \sqsubseteq_{\mathcal{H}^+}$, while this is not the case for filter models. In other words, being extensional and preserving ω -polarities are sufficient conditions for a relational graph model to be fully abstract for \mathcal{H}^+ . We will now provide conditions that are both necessary and sufficient.

6. CHARACTERIZING FULLY ABSTRACT RELATIONAL MODELS OF \mathcal{H}^+

In this section we provide a characterization of those relational graph models that are (inequationally) fully abstract for \mathcal{H}^+ . We first introduce the notion of λ -König relational graph model (Definition 6.5), and show that a relational graph model \mathcal{D} is extensional and λ -König exactly when the induced inequational theory is the preorder $\sqsubseteq_{\mathcal{H}^+}$ (Theorem 6.8).

Since our proof technique does not rely on the quantitative properties of relational graph models, hereafter we rather prefer to use the categorical interpretation.

6.1. Lambda König Relational Graph Models. Before entering into the technicalities we try to give the intuition behind our condition. The main issue is to find suitable conditions for assuring that if M, N have the same interpretation in a relational graph model \mathcal{D} then $M =_{\mathcal{H}^+} N$, equivalently that $M \neq_{\mathcal{H}^+} N$ implies $|M|^{\mathcal{D}} \neq |N|^{\mathcal{D}}$. Now, the idea behind Theorem 2.14 is that two λ -terms M, N are equal in \mathcal{H}^* , but different in \mathcal{H}^+ , when there is a (possibly *virtual*⁴) position $\sigma \in \mathbb{N}^{<\omega}$ such that, say, $\text{BT}(M)_{\sigma} = x$ while $\text{BT}(N)_{\sigma}$ is an infinite η -expansion of x following some $T \in \mathbb{T}_{\text{rec}}^{\infty}$. As a consequence of this fact, our models need to separate x from any $\mathbf{J}_T x$ for $T \in \mathbb{T}_{\text{rec}}^{\infty}$ in order to be fully abstract for \mathcal{H}^+ .

⁴Intuitively, a position σ is virtual if it does not belong to $\text{BT}(M)$, but rather to one of its η -expansions. For more details we refer to [6, §10.3].

Notice now that in any extensional relational graph model \mathcal{D} , every element α_0 is equal to an arrow, so one can always try to unfold α following a function f , starting with:

$$\alpha_0 = a_0 \rightarrow \cdots \rightarrow a_{f(0)} \rightarrow \beta$$

If there is an $\alpha_1 \in a_{f(0)}$, then one can keep unfolding:

$$\alpha_1 = a'_0 \rightarrow \cdots \rightarrow a'_{f(1)} \rightarrow \beta'$$

and so on. More generally, at level ℓ we have $\alpha_\ell = b_0 \rightarrow \cdots \rightarrow b_{f(\ell)} \rightarrow \alpha'$ for some $b_i \in \mathcal{M}_f(D)$ and $\alpha' \in D$ and as long as there exist an $\alpha_{\ell+1} \in a_{f(\ell)}$, we can keep unfolding it at level $\ell + 1$. There are now two possibilities.

- (1) If this process continues indefinitely, then we consider that α can actually be unfolded following f .
- (2) Otherwise, if at some level ℓ we have $a_{f(\ell)} = \omega$, then the process is forced to stop and we consider that α cannot be unfolded following f .

Now, as $T \in \mathbb{T}_{\text{rec}}^\infty$ is a finitely branching infinite tree, by König's lemma there exists an infinite path f in $\text{BT}(\mathbf{J}_T)$. Since the interpretation of \mathbf{J}_T is inductively defined (rather than coinductively), we will then have that $[\alpha] \rightarrow \alpha \notin |\mathbf{J}_T|$ for any α whose unfolding can actually follow f .

In some sense such an α is *witnessing within the model* the existence of an infinite path f in T , and therefore in \mathbf{J}_T . The following is a coinductive definition of such a witness.

Recall from Definition 1.3, that $\Pi(T)$ denotes the set of infinite paths of a tree $T \in \mathbb{T}^\infty$.

Definition 6.1. Let \mathcal{D} be an rgm, $T \in \mathbb{T}_{\text{rec}}^\infty$ and $f \in \Pi(T)$.

- An element $\alpha \in D$ is a *witness for T (in \mathcal{D}) following f* if there exist $a_0, \dots, a_{f(0)} \in \mathcal{M}_f(\mathcal{D})$ and $\alpha' \in \mathcal{D}$ such that

$$\alpha = a_0 \rightarrow \cdots \rightarrow a_{f(0)} \rightarrow \alpha'$$

and there is a witness $\beta \in a_{f(0)}$ for $T|_{\langle f(0) \rangle}$ following $f^{\geq 1}$ that maps $k \mapsto f(k+1)$.

- We let $W_{\mathcal{D},f}(T)$ be the set of all witnesses for T in \mathcal{D} following f .
- We say that α is a *witness for T in \mathcal{D}* when there exists an $f \in \Pi(T)$ such that α is a witness for T in \mathcal{D} following f .
- We let $W_{\mathcal{D}}(T)$ be the set of all witnesses for T in \mathcal{D} .

We formalize the intuition given above by showing that $W_{\mathcal{D}}(T)$ is constituted by those $\alpha \in D$ such that $[\alpha] \rightarrow \alpha \notin |\mathbf{J}_T|$. We first prove the following technical lemmas.

Lemma 6.2. Let \mathcal{D} be an rgm. For all $T \in \mathbb{T}_{\text{rec}}^\infty$ and $x \in \text{Var}$ we have $|\mathbf{J}_T x|_x^{\mathcal{D}} \subseteq |x|_x^{\mathcal{D}}$.

Proof. Let $(a, \alpha) \in |\mathbf{J}_T x|_x$. By Theorem 4.15 there is $t \in \text{BT}^*(\mathbf{J}_T x)$ such that $(a, \alpha) \in |t|_x$. Proceeding by induction on t , we show that $a = [\alpha]$. The case $t = \perp$ is vacuous.

Consider $t = \lambda z_0 \dots z_{T(\varepsilon)-1}. x t_0 \cdots t_{T(\varepsilon)-1}$ where $t_i \in \text{BT}(\mathbf{J}_T|_{\langle i \rangle} z_i)$. By Definition 3.11(ii) we have $(a, \alpha) \in |t|_x$ if and only if $\alpha = a_0 \rightarrow \cdots \rightarrow a_{T(\varepsilon)-1} \rightarrow \alpha'$ for some $a_i = [\alpha_{i,1}, \dots, \alpha_{i,k_i}]$ and $((a, a_0, \dots, a_{T(\varepsilon)-1}), \alpha') \in |x t_0 \cdots t_{T(\varepsilon)-1}|_{x, z_0, \dots, z_{T(\varepsilon)-1}}$. By Definition 3.11(i),(iii) we get $a = [b_0 \rightarrow \cdots \rightarrow b_{T(\varepsilon)-1} \rightarrow \alpha']$ where $b_i = \sum_{j=1}^{k_i} b_{i,j}$ for some $b_{i,j}$ such that $(b_{i,j}, \alpha_{i,j}) \in |t_i|_{z_i}$. By the inductive hypothesis we have $b_{i,j} = [\alpha_{i,j}]$. Therefore $b_i = [\alpha_{i,1}, \dots, \alpha_{i,k_i}] = a_i$ which in its turn entails $a = [b_0 \rightarrow \cdots \rightarrow b_{T(\varepsilon)-1} \rightarrow \alpha'] = [a_0 \rightarrow \cdots \rightarrow a_{T(\varepsilon)-1} \rightarrow \alpha'] = [\alpha]$. \square

Lemma 6.3. Let \mathcal{D} be an rgm. For all $T \in \mathbb{T}_{\text{rec}}^\infty$, $\alpha \in W_{\mathcal{D}}(T)$ and $t \in \text{BT}^*(\mathbf{J}_T x)$ we have $([\alpha], \alpha) \notin |t|_x^{\mathcal{D}}$.

Proof. We proceed by induction on the size $\#t$ of t .

Case $\#t = 0$. This case is trivial since $t = \perp$ and $|\perp|_x = \emptyset$.

Case $\#t > 0$. Then $t = \lambda z_0 \dots z_{T(\varepsilon)-1}.xt_0 \dots t_{T(\varepsilon)-1}$ where each $t_i \in \text{BT}^*(\mathbf{J}_{T \upharpoonright_{\{i\}}} z_i)$ is such that $\#t_i < \#t$. By Definition 3.11(ii) we have $([\alpha], \alpha) \in |t|_x$ if and only if $\alpha = a_0 \rightarrow \dots \rightarrow a_{T(\varepsilon)-1} \rightarrow \alpha'$ for some $a_i = [\alpha_{i,1}, \dots, \alpha_{i,k_i}]$ and $(([\alpha], a_0, \dots, a_{T(\varepsilon)-1}), \alpha') \in |xt_0 \dots t_{T(\varepsilon)-1}|_{x, z_0, \dots, z_{T(\varepsilon)-1}}$. As $|t_i|_{z_i} \subseteq |z_i|_{z_i}$ by Lemma 6.2, we obtain $([\alpha_{i,j}], \alpha_{i,j}) \in |t_i|_{z_i}$ for all $i \leq T(\varepsilon) - 1$ and $j \leq k_i$. Since $\alpha \in W_{\mathcal{D},f}(T)$ for some f , there exists a witness $\alpha_{f(0),j} \in a_{f(0)}$ for $T \upharpoonright_{\langle f(0) \rangle}$ following $f^{\geq 1}$. By $\alpha_{f(0),j} \in W_{\mathcal{D}}(T \upharpoonright_{\langle f(0) \rangle})$ and the induction hypothesis we get $([\alpha_{f(0),j}], \alpha_{f(0),j}) \notin |t_{f(0)}|_{z_{f(0)}}$, which is a contradiction. \square

By applying the Approximation Theorem we get the following characterization of $W_{\mathcal{D}}(T)$.

Proposition 6.4. For any extensional rgm \mathcal{D} and any tree $T \in \mathbb{T}_{\text{rec}}^\infty$:

$$W_{\mathcal{D}}(T) = \{\alpha \in D \mid ([\alpha], \alpha) \notin |\mathbf{J}_T x|_x\}.$$

Proof. (\subseteq) Follows immediately from the Approximation Theorem 4.15 and from Lemma 6.3.

(\supseteq) Let $\alpha \in D$ such that $([\alpha], \alpha) \notin |\mathbf{J}_T x|_x$. We coinductively construct a path f such that $\alpha \in W_f(T)$. As T is infinite we have $\mathbf{J}_T x =_{\beta} \lambda z_0 \dots z_n.x(\mathbf{J}_{T \upharpoonright_{\{0\}}} z_0) \dots (\mathbf{J}_{T \upharpoonright_{\{n\}}} z_n)$ and since \mathcal{D} is extensional $\alpha = a_0 \rightarrow \dots \rightarrow a_n \rightarrow \alpha'$. From $([\alpha], \alpha) \notin |\mathbf{J}_T x|_x$ and the soundness we get $([\alpha], \alpha) \notin |\lambda z_0 \dots z_n.x(\mathbf{J}_{T \upharpoonright_{\{0\}}} z_0) \dots (\mathbf{J}_{T \upharpoonright_{\{n\}}} z_n)|_x$. Therefore there exist an index $k \leq n$ such that $a_k \neq \omega$ and an element $\beta \in a_k$ such that $([\beta], \beta) \notin |\mathbf{J}_{T \upharpoonright_{\{k\}}} z_k|_{z_k}$. By the coinductive hypothesis, there is a function g such that $\beta \in W_{\mathcal{D},g}(T \upharpoonright_{\{k\}})$. We conclude since $\alpha \in W_{\mathcal{D},f}(T)$ where f is the function defined as follows: $f(0) = k$ and $f(n+1) = g(n)$ for all $n \in \mathbb{N}$. \square

It should be now clear that a relational graph model \mathcal{D} , to be fully abstract for \mathcal{H}^+ , needs for every λ -definable infinite η -expansion of the identity an element in D witnessing its infinite path, which exists by König's lemma. This justifies the definition below.

Definition 6.5 (λ -König models). An rgm \mathcal{D} is λ -König if for every $T \in \mathbb{T}_{\text{rec}}^\infty$, $W_{\mathcal{D}}(T) \neq \emptyset$.

6.2. The Characterization of Fully Abstract Models for \mathcal{H}^+ . We will mainly focus on the λ -König condition, since the extensionality is clearly necessary, as $\lambda\eta \subseteq \mathcal{H}^+$.

We start by showing that, if \mathcal{D} is an extensional λ -König relational graph model, then $\text{Th}_{\sqsubseteq}(\mathcal{D}) = \sqsubseteq_{\mathcal{H}^+}$. Indeed, since every $T \in \mathbb{T}_{\text{rec}}^\infty$ has a non-empty set of witnesses $W_{\mathcal{D}}(T)$, by Proposition 6.4, there is an element $\alpha \in W_{\mathcal{D}}(T)$ such that $[\alpha] \rightarrow \alpha \notin |\mathbf{I}| - |\mathbf{J}_T|$. Thus, \mathcal{D} separates \mathbf{I} from all the \mathbf{J}_T 's for $T \in \mathbb{T}_{\text{rec}}^\infty$.

Theorem 6.6 (Inequational Full Abstraction). Let \mathcal{D} be an extensional λ -König rgm, then:

$$M \sqsubseteq_{\mathcal{H}^+} N \iff \mathcal{D} \models M \sqsubseteq N$$

Proof. (\Rightarrow) This follows directly from Corollary 4.17.

(\Leftarrow) We assume, by the way of contradiction, that $\mathcal{D} \models M \sqsubseteq N$ but $M \not\sqsubseteq_{\mathcal{H}^+} N$. By the maximality of $\sqsubseteq_{\mathcal{H}^*}$ shown in Lemma 2.3 and the fact that $|M|_{\vec{x}} \subseteq |N|_{\vec{x}}$ we must have $M \sqsubseteq_{\mathcal{H}^*} N$. By Theorem 2.14 there exists a context $C[-]$ such that $C[M] =_{\beta\eta} \mathbf{I}$ and $C[N] =_{\beta} \mathbf{J}_T$ for some $T \in \mathbb{T}_{\text{rec}}^\infty$. By monotonicity of the interpretation $|-|$ and since $\mathcal{B}\eta \subseteq \mathcal{H}^+ \subseteq \text{Th}(\mathcal{D})$ by Corollary 4.17, we have $|\mathbf{I}| = |C[M]| \subseteq |C[N]| = |\mathbf{J}_T|$. We derive a contradiction by applying Proposition 6.4. \square

We now show the converse, namely that if a relational graph model is (inequationally) fully abstract for \mathcal{H}^+ , then it is extensional and λ -König.

Theorem 6.7. Let \mathcal{D} be an rgm. If $\text{Th}_{\sqsubseteq}(\mathcal{D}) = \sqsubseteq_{\mathcal{H}^+}$ or $\text{Th}(\mathcal{D}) = \mathcal{H}^+$ then \mathcal{D} is extensional and λ -König.

Proof. Obviously \mathcal{D} must be extensional since \mathcal{H}^* is an extensional λ -theory. By the way of contradiction, we suppose that it is not λ -König. Then there is $T \in \mathbb{T}_{\text{rec}}^\infty$ such that $W_{\mathcal{D}}(T) = \emptyset$ and, by Proposition 6.4, we get $|\mathbf{I}| = |\mathbf{J}_T|$. This is impossible since $\mathbf{I} \not\sqsubseteq_{\mathcal{H}^+} \mathbf{J}_T$. \square

From Theorems 6.6 and Theorem 6.7 we get the main result of this section.

Theorem 6.8. For an rgm \mathcal{D} , the following are equivalent:

- (i) \mathcal{D} is extensional and λ -König,
- (ii) \mathcal{D} is inequationally fully abstract for $\sqsubseteq_{\mathcal{H}^+}$,
- (iii) \mathcal{D} is fully abstract for \mathcal{H}^+ .

The following result first appeared in [62].

Corollary 6.9. The model \mathcal{D}_* of Example 3.10 is inequationally fully abstract for Morris's preorder $\sqsubseteq_{\mathcal{H}^+}$. In particular $\text{Th}(\mathcal{D}_*) = \mathcal{H}^+$.

7. CHARACTERIZING FULLY ABSTRACT RELATIONAL MODELS OF \mathcal{H}^*

In this section we provide a characterization of those relational graph models that are (inequationally) fully abstract for \mathcal{H}^* . At this purpose, we introduce the notion of *hyperimmune* relational graph model (Definition 7.10), which is in some sense dual to the notion of λ -König. We prove that a relational graph model \mathcal{D} is extensional and hyperimmune exactly when the induced inequational theory is the preorder $\sqsubseteq_{\mathcal{H}^*}$ (Theorem 7.15).

The technique in this section is Böhm-like tree oriented, therefore it is convenient to fix some notations concerning Böhm-like trees and their interpretation.

Notation 7.1. We simply denote by \mathbf{J}_T^x the tree $\text{BT}(\mathbf{J}_T x)$, where x is a fresh variable. Given a Böhm-like tree V , we write V^* for the set $\{t \in \text{NF}_{\beta\perp} \mid t \leq_{\perp} V\}$ of its finite approximants and we set $\llbracket V \rrbracket^{\mathcal{D}} = \bigcup_{t \in V^*} \llbracket t \rrbracket^{\mathcal{D}}$.

7.1. Decomposing Infinite η -Expansions. When considering Böhm trees of λ -terms, the infinite η -expansion \leq_{∞}^{η} can be decomposed into the finitary one \leq^{η} followed by a more restricted infinite η -expansion $\leq_{!}^{\eta}$ that only allows to η -expand variables (Lemma 7.6).

Remember that the difference between \leq_{∞}^{η} and \leq^{η} lies in the fact that the former allows countably many possibly infinite η -expansions, whereas the latter only countably many finite ones. As first noticed by Severi and de Vries in their recent work on the infinitary λ -calculus [78], in a way this difference only concerns η -expansions of variables. Consider for instance $yy \not\leq^{\eta} \lambda x.y\mathbf{J}^y\mathbf{J}^x$ and $yy \leq_{\infty}^{\eta} \lambda x.y\mathbf{J}^y\mathbf{J}^x$. The tree $\lambda x.y\mathbf{J}^y\mathbf{J}^x$ is an infinite η -expansion of yy , which is not a variable. Nevertheless, one can narrow down to infinite η -expansions of the variables x and y , by noticing that $yy \leq^{\eta} \lambda x.yyx \leq_{\infty}^{\eta} \lambda x.y\mathbf{J}^y\mathbf{J}^x$.

Definition 7.2. The relation $\leq_{!}^{\eta}$ on Böhm-like trees is coinductively given by:

- $\perp \leq_{!}^{\eta} \perp$,

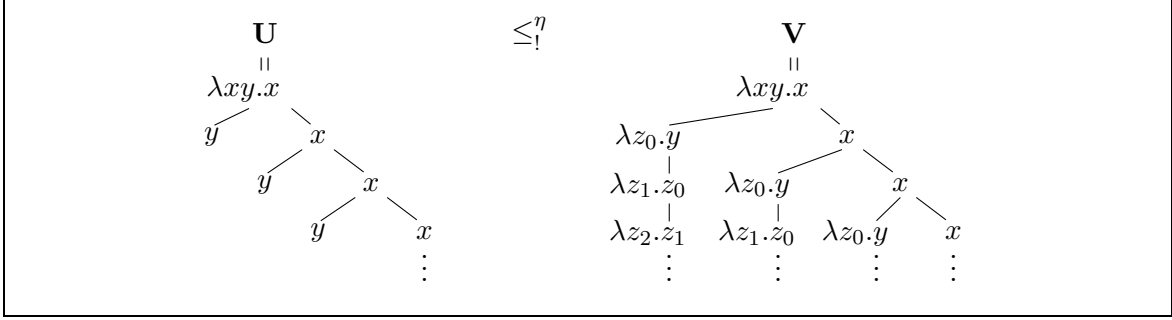


Figure 5: An example of infinitely many $\eta!$ -reductions.

- $x \leq!^\eta \mathbf{J}_T^x$ for $T \in \mathbb{T}_{\text{rec}}^\infty$,
- $\lambda x_1 \dots x_n. x_i U_1 \dots U_k \leq!^\eta \lambda x_1 \dots x_n. x_i V_1 \dots V_k$ if $k, n \in \mathbb{N}$ and $U_j \leq!^\eta V_j$ for all $j \leq k$.

Example 7.3. We have $\lambda x. y y x \leq!^\eta \lambda x. y \mathbf{J}^y \mathbf{J}^x$, whereas $y y \not\leq!^\eta \lambda x. y \mathbf{J}^y \mathbf{J}^x$.

Clearly $\leq!^\eta$ is a subrelation of \leq_∞^η , as it is the case for \leq^η . Also notice that $\leq!^\eta$ and \leq^η are completely orthogonal relations, in the sense that $U \leq^\eta V$ and $U \leq!^\eta V$ imply $U = V$.

For technical reasons we also need an *inductive* version of the relation $\leq!^\eta$, that we denote by $\eta! \leftarrow$ borrowing the notation from [78]. Intuitively $U \eta! \leftarrow V$ means that V is obtained from U by performing finitely many infinite η -expansions of variables. However our relation is furthermore restricted to infinite η -expansions of the identity following some recursive trees, while Severi and de Vrijes's $\eta!$ -rule is more general.

It turns out that hyperimmune relational graph models cannot distinguish between the relation $U \eta! \leftarrow V$ and its coinductive version $U \leq!^\eta V$, in the sense expressed by the equivalence (iii \iff iv) in Proposition 7.12.

Definition 7.4. The relation $\eta! \leftarrow$ on Böhm-like trees is inductively defined as follows:

- $\perp \eta! \leftarrow \perp$,
- $x \eta! \leftarrow \mathbf{J}_T^x$ for $T \in \mathbb{T}_{\text{rec}}^\infty$,
- $\lambda x_1 \dots x_n. y U_1 \dots U_k \eta! \leftarrow \lambda x_1 \dots x_n. y V_1 \dots V_k$ if $k, n \in \mathbb{N}$ and $U_i \eta! \leftarrow V_i$ for all $i \leq k$.

Alternatively, one can define $\rightarrow_{\eta!}$ as the transitive-reflexive and contextual closure of

$$(\eta!) \quad \mathbf{J}_T^x \rightarrow_{\eta!} x \quad \text{for all } T \in \mathbb{T}_{\text{rec}}^\infty.$$

Example 7.5. Let $\mathbf{U} = \text{BT}(\lambda xy. \mathbf{Y}(\lambda u. xyu))$ and $\mathbf{V} = \text{BT}(\lambda xy. \mathbf{Y}(\lambda u. x(\mathbf{J}^y u)))$. These two trees are depicted in Figure 5. We have that $\mathbf{U} \leq!^\eta \mathbf{V}$ while $\mathbf{U} \eta! \not\leftarrow \mathbf{V}$, because \mathbf{V} is obtained from \mathbf{U} by performing an infinite amount of $\eta!$ -expansions of variables.

Lemma 7.6. (Decomposition of \leq_∞^η) Let $M, N \in \Lambda$. Then $\text{BT}(M) \leq_\infty^\eta \text{BT}(N)$ if and only if there exists a Böhm-like tree W such that $\text{BT}(M) \leq^\eta W \leq!^\eta \text{BT}(N)$.

Proof. (\Rightarrow) By transitivity of \leq_∞^η , using the fact that both \leq^η and $\leq!^\eta$ are contained in \leq_∞^η .

(\Leftarrow) We construct W coinductively.

In case M and N are unsolvable we just take $W = \perp$.

Otherwise, $M =_\beta \lambda \vec{x}. x_i M_1 \dots M_k$ and $N =_\beta \lambda \vec{z}. z_1 \dots z_m. x_i N_1 \dots N_k P_1 \dots P_m$ where $\text{BT}(M_j) \leq_\infty^\eta \text{BT}(N_j)$ for all $j \leq k$ and $z_\ell \leq_\infty^\eta \text{BT}(P_\ell)$ for all $\ell \leq m$. By the coinductive hypothesis, for all j there exists W_j such that $\text{BT}(M_j) \leq^\eta W_j \leq!^\eta \text{BT}(N_j)$. We then set $W = \lambda \vec{x} z_1 \dots z_m. W_1 \dots W_n z_1 \dots z_m$. Clearly $\text{BT}(M) \leq^\eta W$. In order to show that $W \leq!^\eta \text{BT}(N)$ holds we have to prove, for all $\ell \leq m$, that $\text{BT}(P_\ell) = \mathbf{J}_{T_\ell}^{z_\ell}$ for some $T_\ell \in \mathbb{T}_{\text{rec}}^\infty$. Since $z_\ell \leq_\infty^\eta \text{BT}(P_\ell)$, we conclude by Proposition 2.9. \square

As shown in [78], the decomposition of \leq_∞^η could be extended to all Böhm-like trees using possibly non-recursive infinite η -expansions of x in the definition of $\leq_!^\eta$. Since here we use $\leq_!^\eta$ in connection with hyperimmune relational graph models (Proposition 7.12), a semantic notion only concerning recursive trees, it is crucial to use the restricted version.

Lemma 7.7. Let U, V be two Böhm-like trees such that $U \leq_!^\eta V$ and let $t \in U^*$. Then there exists a Böhm-like tree W such that $U \leq_!^\eta W \eta^! \leftarrow V$ and $t \in W^*$.

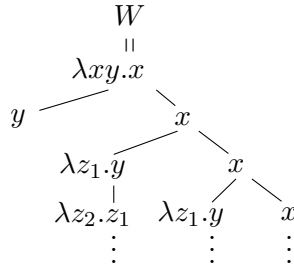
Proof. We proceed by induction on t .

If $t = \perp$ it suffices to take $W = V$.

If $t = U = x$ and $V = \mathbf{J}_T^x$ we get the thesis by taking either $W = V$ or $W = U$.

If $t = \lambda \vec{x}. x_i t_1 \cdots t_k$, then $U = \lambda \vec{x}. x_i U_1 \cdots U_k$ and $V = \lambda \vec{x}. x_i V_1 \cdots V_k$ where $t_j \in U_j^*$ and $U_j \leq_!^\eta V_j$ for all $j \leq k$. By induction hypothesis for each j we get some W_j such that $U_j \leq_!^\eta W_j \eta^! \leftarrow V_j$ and $t_j \leq_\perp W_j$. We conclude by setting $W = \lambda \vec{x}. x_i W_1 \cdots W_k$. \square

Example 7.8. Let U, V be the trees from Example 7.5 (and Figure 5) and let $t = \lambda xy. xy \perp \in U^*$. A possible Böhm-like tree W given by Lemma 7.7 is the following:



Actually, the statement of Lemma 7.7 concerning $\eta^!$ -expansions can be generalized to generic η -expansions as follows.

Lemma 7.9. Let U, V be two Böhm-like trees such that $U \leq_\infty^\eta V$ and let $t \in U^*$. Then there exists a Böhm-like tree W such that $U \leq_\infty^\eta W \leq^\eta V$ and $t \in W^*$.

Proof. The Böhm-like tree W can easily be constructed by induction on t . \square

7.2. Hyperimmune Relational Graph Models. In Section 6 we exploited the Morris Separation (Theorem 2.14) to reduce the problem of being fully abstract for \mathcal{H}^+ to the property $\llbracket x \rrbracket \neq \llbracket \mathbf{J}_T x \rrbracket$, namely $\mathcal{W}_\mathcal{D}(T) = \llbracket x \rrbracket - \llbracket \mathbf{J}_T x \rrbracket \neq \emptyset$, for every tree $T \in \mathbb{T}_{\text{rec}}^\infty$. The notion of λ -König relational graph model provided that. Here there is a similar phenomenon: we exploit the decomposition seen above (Lemma 7.6) to reduce the full abstraction for \mathcal{H}^* to the property $\llbracket x \rrbracket = \llbracket \mathbf{J}_T x \rrbracket$, namely $\mathcal{W}_\mathcal{D}(T) = \llbracket x \rrbracket - \llbracket \mathbf{J}_T x \rrbracket = \emptyset$, for every $T \in \mathbb{T}_{\text{rec}}^\infty$. This is the intuition behind the following definition, which is some kind of dual of λ -König.

Definition 7.10 (Hyperimmune models). An rgm \mathcal{D} is *hyperimmune* if for every $T \in \mathbb{T}_{\text{rec}}^\infty$ $\mathcal{W}_\mathcal{D}(T) = \emptyset$.

The name refers to a standard concept in computability theory: a function $f : \mathbb{N} \rightarrow \mathbb{N}$ is called *hyperimmune* if it is not bounded (upwardly) by any recursive function. One can prove that a relational graph model \mathcal{D} is hyperimmune exactly when it only admits witnesses that follow hyperimmune functions. This observation justifies the choice of the terminology. The notion of hyperimmunity first appeared in these terms in [15] for Krivine's models.

Example 7.11. The model \mathcal{D}_ω of Example 3.10 is hyperimmune. As a matter of fact, since the model is freely generated by the equation $\star = \omega \rightarrow \star$, it is easy to verify that no element of \mathcal{D}_ω can be a witness for any $T \in \mathbb{T}_{\text{rec}}^\infty$ following any infinite path f .

In the hypothesis of extensionality, this notion admits some additional characterizations.

Proposition 7.12. Let \mathcal{D} be an extensional rgm. The following statements are equivalent:

- (i) \mathcal{D} is hyperimmune,
- (ii) $\llbracket x \rrbracket \subseteq \llbracket \mathbf{J}_T x \rrbracket$ for all $T \in \mathbb{T}_{\text{rec}}^\infty$,
- (iii) $U \eta^! \leftarrow V$ implies $\llbracket U \rrbracket \subseteq \llbracket V \rrbracket$ for all Böhm-like trees U, V ,
- (iv) $U \leq_!^\eta V$ implies $\llbracket U \rrbracket \subseteq \llbracket V \rrbracket$ for all Böhm-like trees U, V .

Proof. (i \iff ii) By Proposition 6.4 and Corollary 4.9 an extensional rgm \mathcal{D} is hyperimmune if and only if, for all $T \in \mathbb{T}_{\text{rec}}^\infty$, we have that $\llbracket x \rrbracket - \llbracket \mathbf{J}_T x \rrbracket = \{\alpha \in \mathcal{D} \mid x : [\alpha] \not\vdash \mathbf{J}_T x : \alpha\} = W_{\mathcal{D}}(T) = \emptyset$. This is equivalent to requiring that $\llbracket x \rrbracket \subseteq \llbracket \mathbf{J}_T x \rrbracket$ for all $T \in \mathbb{T}_{\text{rec}}^\infty$.

(ii \Rightarrow iii) By a straightforward induction on the derivation of $U \eta^! \leftarrow V$.

(iii \Rightarrow ii) Trivial.

(iii \Rightarrow iv) Suppose that there exist two Böhm-like trees U, V such that $U \leq_!^\eta V$ and $\llbracket U \rrbracket \not\subseteq \llbracket V \rrbracket$. Since $\llbracket U \rrbracket = \bigcup_{t \in U^*} \llbracket t \rrbracket$, there is a $t \in U^*$ such that $\llbracket t \rrbracket \not\subseteq \llbracket V \rrbracket$. By Lemma 7.7 there exists $W \eta^! \leftarrow V$ such that $t \in W^*$. Since $\llbracket W \rrbracket = \bigcup_{t \in W^*} \llbracket t \rrbracket$, we get $\llbracket W \rrbracket \not\subseteq \llbracket V \rrbracket$.

(iv \Rightarrow iii) Trivial. \square

Lemma 7.13. Let \mathcal{D} be an extensional rgm and U, V be two Böhm-like trees. Then $V \leq_\infty^\eta U$ implies $\llbracket U \rrbracket \subseteq \llbracket V \rrbracket$.

Proof. By Lemma 7.9, if $t \in U^*$ then $t \in W^*$ for some $W \leq^\eta V$. So $\llbracket t \rrbracket \subseteq \llbracket W \rrbracket \subseteq \llbracket V \rrbracket$, where the second inclusion holds by extensionality. Since $\llbracket U \rrbracket = \bigcup_{t \in U^*} \llbracket t \rrbracket$, we get $\llbracket U \rrbracket \subseteq \llbracket V \rrbracket$. \square

In general, the inverse hypothesis $U \leq_\infty^\eta V$ does not imply $\llbracket U \rrbracket \subseteq \llbracket V \rrbracket$, even in presence of extensionality. This implication only holds when the model is moreover hyperimmune.

Lemma 7.14. Let \mathcal{D} be an extensional and hyperimmune rgm and $M, N \in \Lambda$. Then $\text{BT}(M) \leq_\infty^\eta \text{BT}(N)$ implies $\llbracket M \rrbracket \subseteq \llbracket N \rrbracket$.

Proof. By Lemma 7.6 there exists a Böhm-like tree W such that $\text{BT}(M) \leq^\eta W \leq_!^\eta \text{BT}(N)$. Then we have $\llbracket \text{BT}(M) \rrbracket \subseteq \llbracket W \rrbracket$ by extensionality and $\llbracket W \rrbracket \subseteq \llbracket \text{BT}(N) \rrbracket$ by the characterization iv of hyperimmunity provided by Proposition 7.12. By transitivity we obtain $\llbracket \text{BT}(M) \rrbracket \subseteq \llbracket \text{BT}(N) \rrbracket$, so we conclude $\llbracket M \rrbracket \subseteq \llbracket N \rrbracket$ by Theorem 4.15. \square

7.3. The Characterization of Fully Abstraction Models for \mathcal{H}^* . The following theorem constitutes the main result of the section. It is actually an adaptation to relational graph models of the characterization of fully abstract Krivine's models provided in [15, 16].

Theorem 7.15. Let \mathcal{D} be an rgm. The following statements are equivalent:

- (i) \mathcal{D} is extensional and hyperimmune,
- (ii) \mathcal{D} is inequationally fully abstract for $\sqsubseteq_{\mathcal{H}^*}$,
- (iii) \mathcal{D} is fully abstract for \mathcal{H}^* .

Proof. (i \Rightarrow ii) We must prove that $M \sqsubseteq_{\mathcal{H}^*} N$ if and only if $\llbracket M \rrbracket \subseteq \llbracket N \rrbracket$. The right-to-left implication is true for all rgm's, since these are sensible (Corollary 4.16) and $\sqsubseteq_{\mathcal{H}^*}$ is the maximal sensible inequational theory. Let us prove the left-to-right implication.

By Theorem 2.5 the hypothesis $M \sqsubseteq_{\mathcal{H}^*} N$ means that $\text{BT}(M) \leq_{\infty}^{\eta} U \leq_{\perp} V \geq_{\infty}^{\eta} \text{BT}(N)$ for some Böhm-like trees U and V . In particular U can be taken of the form $U = \text{BT}(P)$ for some $P \in \Lambda$ (see [6, Ex. 10.6.7]). Then we have

$$\begin{aligned}
\llbracket M \rrbracket &\subseteq \llbracket P \rrbracket && \text{by Lemma 7.14} \\
&= \llbracket U \rrbracket && \text{by Theorem 4.15} \\
&\subseteq \llbracket V \rrbracket && \text{by def. of } \llbracket - \rrbracket \text{ for Böhm-like trees} \\
&\subseteq \llbracket \text{BT}(N) \rrbracket && \text{by Lemma 7.13} \\
&= \llbracket N \rrbracket && \text{by Theorem 4.15.}
\end{aligned}$$

(ii \Rightarrow iii) Trivial.

(iii \Rightarrow i) The theory \mathcal{H}^* is extensional, so that is the case for any fully abstract rgm. Moreover, the theory \mathcal{H}^* satisfies $x \sqsubseteq_{\mathcal{H}^*} \mathbf{J}_T x$ for all $T \in \mathbb{T}_{\text{rec}}^{\infty}$. So the model is hyperimmune by the characterization ii of hyperimmunity provided by Proposition 7.12. \square

The following result first appeared in [60].

Corollary 7.16. *The model \mathcal{D}_{ω} of Example 3.10 is inequationally fully abstract for $\sqsubseteq_{\mathcal{H}^*}$. In particular $\text{Th}(\mathcal{D}_{\omega}) = \mathcal{H}^*$.*

8. CONCLUSIONS

We have studied the class of the relational graph models living inside the relational semantics of λ -calculus, and proved that they all enjoy the Approximation Theorem. We exhibited a model inducing the minimum relational (in)equational graph theory, and provided sufficient and necessary conditions for a relational graph model to be fully abstract for \mathcal{H}^+ (resp. \mathcal{H}^*). We conclude presenting some open problems that we consider interesting.

Problem 1. It is well known that the λ -theory \mathcal{H}^* satisfies the ω -rule [6, Def. 4.1.10], and the analogous result was recently proved for \mathcal{H}^+ in [17]. Does every extensional graph model satisfy the ω -rule?

Problem 2. Are all λ -theories in the interval $[\mathcal{H}^+, \mathcal{H}^*]$ relational graph theories? If it is not the case, is it possible to provide a characterization of the representable ones?

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APPENDIX A. TECHNICAL APPENDIX

This technical appendix is devoted to prove the Weighted Substitution Lemma and the Weighted Subject Reduction, that have been stated in Section 4. We first introduce some auxiliary notions that will be useful in the subsequent proofs.

Definition A.1. Let $M, N \in \Lambda_\perp$ and \mathcal{D} be an rgm.

- Given $\pi_0 \blacktriangleright \Gamma \vdash M : [\beta_1, \dots, \beta_n] \rightarrow \alpha$ and $\pi_i \blacktriangleright \Delta_i \vdash N : \beta_i$ for all $1 \leq i \leq n$, we let $\text{App}(\pi_0, \{\pi_i\}_{i=1}^n)$ be the derivation tree of $\Gamma + (\sum_{i=1}^n \Delta_i) \vdash MN : \alpha$ obtained by applying the rule **app** to those premises.
- Similarly, given $\pi \blacktriangleright \Gamma, x : a \vdash M : \beta$ we define $\text{Lam}(x, \pi)$ as the derivation obtained by applying the rule **lam** to the derivation π .

Lemma 4.10 (Weighted Substitution Lemma). Let $M, N \in \Lambda_\perp$. Consider some derivations $\pi_0 \blacktriangleright \Gamma_0, x : [\beta_1, \dots, \beta_n] \vdash M : \alpha$ for $n \in \mathbb{N}$ and $\pi_i \blacktriangleright \Gamma_i \vdash N : \beta_i$ for all $1 \leq i \leq n$. Then there exists $\pi \blacktriangleright \sum_{i=0}^n \Gamma_i \vdash M\{N/x\} : \alpha$ such that $\#app(\pi) = \sum_{i=0}^n \#app(\pi_i)$.

Proof. **Case** $M = \perp$. This case does not need to be considered, as \perp cannot be typed.

Case $M = y \neq x$. Then $\pi_0 \blacktriangleright \Gamma_0, x : [\beta_1, \dots, \beta_n] \vdash y : \alpha$ entails $n = 0$ and $\Gamma_0 = y : \alpha$. Hence the judgment $\sum_{i=0}^n \Gamma_i \vdash M\{N/x\} : \alpha$ is nothing but $y : \alpha \vdash y : \alpha$ and we can take $\pi = \pi_0$. Clearly $\#app(\pi) = 0 = \#app(\pi_0) = \sum_{i=0}^n \#app(\pi_i)$.

Case $M = x$. Then $\Gamma_0, x : [\beta_1, \dots, \beta_n] \vdash x : \alpha$ implies that $n = 1$, $\beta_1 = \alpha$ and Γ_0 is empty. Hence the judgment $\sum_{i=0}^n \Gamma_i \vdash M\{N/x\} : \alpha$ is just $\Gamma_1 \vdash N : \alpha$ and we can take $\pi = \pi_1$. Clearly $\#app(\pi) = \#app(\pi_1) = \sum_{i=0}^n \#app(\pi_i)$.

Case $M = \lambda y.P$. Then there is a derivation π'_0 such that π_0 has the form

$$\frac{\pi'_0 \blacktriangleright \Gamma_0, y : [\alpha_1, \dots, \alpha_n], x : [\beta_1, \dots, \beta_n] \vdash M : \alpha'}{\Gamma_0, x : [\beta_1, \dots, \beta_n] \vdash \lambda y.M : [\alpha_1, \dots, \alpha_n] \rightarrow \alpha'}$$

for $\alpha = [\alpha_1, \dots, \alpha_n] \rightarrow \alpha'$. Notice that $\#app(\pi'_0) = \#app(\pi_0)$. By induction hypothesis, there exists a derivation π' such that

$$\pi' \blacktriangleright (\Gamma_0, y : [\alpha_1, \dots, \alpha_n]) + \sum_{i=1}^n \Gamma_i \vdash M\{N/x\} : \alpha' \quad (4.1)$$

with $\#app(\pi') = \#app(\pi'_0) + \sum_{i=1}^n \#app(\pi_i) = \sum_{i=0}^n \#app(\pi_i)$. By Lemma 4.6 we have $\text{supp}(\Gamma_i) \subseteq \text{FV}(N)$ for all $1 \leq i \leq n$. By α -conversion we assume $y \notin \text{FV}(N)$, thus $y \notin \text{supp}(\Gamma_i)$ for all i . So the judgment in (4.1) is in fact $\sum_{i=0}^n \Gamma_i, y : [\alpha_1, \dots, \alpha_n] \vdash M\{N/x\} : \alpha'$. We can then take $\pi = \text{Lam}(y, \pi') \blacktriangleright \sum_{i=0}^n \Gamma_i \vdash \lambda y.M\{N/x\} : [\alpha_1, \dots, \alpha_n] \rightarrow \alpha'$. The thesis is proved since $\lambda y.M\{N/x\} = (\lambda y.M)\{N/x\}$ and $\#app(\pi) = \#app(\pi') = \sum_{i=0}^n \#app(\pi_i)$.

Case $M = PQ$. Then there are derivations π_{00}, π_{0i} such that π_0 has the form

$$\frac{\pi_{00} \blacktriangleright \Gamma_{00}, x : [\beta_j]_{j \in I_0} \vdash P : [\gamma_1, \dots, \gamma_k] \rightarrow \alpha \quad \pi_{0i} \blacktriangleright \Gamma_{0i}, x : [\beta_j]_{j \in I_i} \vdash Q : \gamma_i \text{ for all } 1 \leq i \leq k}{\sum_{i=0}^k \Gamma_{0i}, x : [\beta_1, \dots, \beta_n] \vdash PQ : \alpha}$$

where $k \in \mathbb{N}$, $\Gamma_0 = \sum_{i=0}^k \Gamma_{0i}$ and $\{I_i\}_{i=0}^k$ is a partition of the set $\{1, \dots, n\}$. By induction hypothesis we get a derivation $\pi'_0 \blacktriangleright \Gamma_{00} + \sum_{j \in I_0} \Gamma_j \vdash P\{N/x\} : [\gamma_1, \dots, \gamma_k] \rightarrow \alpha$ such that $\#app(\pi'_0) = \#app(\pi_{00}) + \sum_{j \in I_0} \#app(\pi_j)$. Also, for all $1 \leq i \leq k$ the induction hypothesis gives a derivation $\pi'_i \blacktriangleright \Gamma_{0i} + \sum_{j \in I_i} \Gamma_j \vdash Q\{N/x\} : \gamma_i$ such that $\#app(\pi'_i) = \#app(\pi_{0i}) + \sum_{j \in I_i} \#app(\pi_j)$.

We take $\pi = \mathbf{App}(\pi'_0, \{\pi'_i\}_{1 \leq i \leq k}) \blacktriangleright \sum_{i=0}^k (\Gamma_{0i} + \sum_{j \in I_i} \Gamma_j) \vdash (P\{N/x\})(Q\{N/x\}) : \alpha$. Clearly $\sum_{i=0}^k (\Gamma_{0i} + \sum_{j \in I_i} \Gamma_j) = \sum_{i=0}^k \Gamma_{0i} + \sum_{i=0}^k \sum_{j \in I_i} \Gamma_j = \Gamma_0 + \sum_{i=1}^n \Gamma_i = \sum_{i=0}^n \Gamma_i$ and $(P\{N/x\})(Q\{N/x\}) = (PQ)\{N/x\}$. Moreover we get that $\#app(\pi) = 1 + \sum_{i=0}^k \#app(\pi'_i) = 1 + \sum_{i=0}^k (\#app(\pi_{0i}) + \sum_{j \in I_i} \#app(\pi_j)) = (1 + \sum_{i=0}^k \#app(\pi_{0i})) + \sum_{i=0}^k \sum_{j \in I_i} \#app(\pi_j) = \#app(\pi_0) + \sum_{i=1}^n \#app(\pi_i) = \sum_{i=0}^n \#app(\pi_i)$. This concludes the proof. \square

Lemma 4.13 (Weighted Subject Reduction). Let $M, M' \in \Lambda_\perp$ be such that $M \xrightarrow{R}_\beta M'$. If $\pi \blacktriangleright \Gamma \vdash M : \alpha$, then there is $\pi' \blacktriangleright \Gamma \vdash M' : \alpha$ such that one of the following cases holds:

- (i) $\#app(\pi') < \#app(\pi)$,
- (ii) $\pi' \simeq \pi$ and there exists $\pi'' \blacktriangleright \Gamma \vdash M\{\perp/R\} : \alpha$ such that $\pi'' \simeq \pi$.

Proof. Let $M = C[R]$ for a one hole $\lambda\perp$ -context $C[-]$. We proceed by induction on $C[-]$.

Case $[-]$. We have $M = R = (\lambda x.P)Q$ and $M' = P\{Q/x\}$. The thesis is then given by Corollary 4.11. More precisely, we are in case (i).

Case $PC[-]$. We have $M = P(C[R])$ and $M' = P(C[R'])$ where $R \rightarrow_\beta R'$. Then, the derivation π has the form

$$\frac{\pi_0 \blacktriangleright \Gamma_0 \vdash P : [\beta_1, \dots, \beta_n] \rightarrow \alpha \quad \pi_i \blacktriangleright \Gamma_i \vdash C[R] : \beta_i \text{ for all } 1 \leq i \leq n}{\sum_{i=0}^n \Gamma_i \vdash P(C[R]) : \alpha}$$

where $n \in \mathbb{N}$ and $\Gamma = \sum_{i=0}^n \Gamma_i$.

For all $1 \leq i \leq n$ by induction hypothesis there is $\pi'_i \blacktriangleright \Gamma_i \vdash C[R'] : \beta_i$ such that either

$$\#app(\pi'_i) < \#app(\pi_i), \tag{4.2}$$

or

$$\pi'_i \simeq \pi_i \simeq \pi''_i \text{ for a derivation } \pi''_i \blacktriangleright \Gamma_i \vdash C[\perp] : \beta_i. \tag{4.3}$$

In this case we take $\pi' = \mathbf{App}(\pi_0, \{\pi'_i\}_{i=1}^n)$.

If every i satisfies (4.3) then $\pi' \simeq \pi$. By taking $\pi'' = \mathbf{App}(\pi_0, \{\pi''_i\}_{i=1}^n)$ we obtain the case (ii) of the thesis. Notice that the eventuality $n = 0$ falls in this case.

If there is an i that satisfies (4.2) then $\#app(\pi') < \#app(\pi)$, so the case (i) is proved.

Case $(C[-])P$. We have $M = (C[R])P$ and $M' = (C[R'])P$ where $R \rightarrow_\beta R'$. Then, the derivation π has the form

$$\frac{\pi_0 \blacktriangleright \Gamma_0 \vdash C[R] : [\beta_1, \dots, \beta_n] \rightarrow \alpha \quad \pi_i \blacktriangleright \Gamma_i \vdash P : \beta_i \text{ for all } 1 \leq i \leq n}{\sum_{i=0}^n \Gamma_i \vdash (C[R])P : \alpha}$$

where $n \in \mathbb{N}$ and $\Gamma = \sum_{i=0}^n \Gamma_i$. By induction hypothesis there exists a derivation $\pi'_0 \blacktriangleright \Gamma_0 \vdash C[R'] : [\beta_1, \dots, \beta_n] \rightarrow \alpha$ such that either $\#app(\pi'_0) < \#app(\pi_0)$, or $\pi'_0 \simeq \pi_0 \simeq \pi''_0$ for some $\pi''_0 \blacktriangleright \Gamma_0 \vdash C[\perp] : [\beta_1, \dots, \beta_n] \rightarrow \alpha$. In the former case, the thesis is proved taking $\pi' = \mathbf{App}(\pi'_0, \{\pi_i\}_{i=1}^n)$ and in the latter also $\pi'' = \mathbf{App}(\pi''_0, \{\pi_i\}_{i=1}^n)$.

Case $\lambda x.C[-]$. We have $M = \lambda x.C[R]$ and $M' = \lambda x.C[R']$, where $R \rightarrow_\beta R'$. Then π has the form

$$\frac{\pi_0 \blacktriangleright \Gamma, x : [\beta_1, \dots, \beta_n] \vdash C[R] : \beta}{\Gamma \vdash \lambda x.C[R] : [\beta_1, \dots, \beta_n] \rightarrow \beta}$$

for $[\beta_1, \dots, \beta_n] \rightarrow \beta = \alpha$. By induction hypothesis there is $\pi'_0 \blacktriangleright \Gamma, x : [\beta_1, \dots, \beta_n] \vdash C[R'] : \beta$ such that either $\#app(\pi'_0) < \#app(\pi_0)$, or $\pi'_0 \simeq \pi_0 \simeq \pi''_0$ for some $\pi''_0 \blacktriangleright \Gamma, x : [\beta_1, \dots, \beta_n] \vdash C[\perp] : \beta$. In the former case, the thesis is proved by taking $\pi' = \mathbf{Lam}(x, \pi'_0)$, and in the latter also $\pi'' = \mathbf{Lam}(x, \pi''_0)$. \square